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THESIS

FORECASTING THE ONSET AND INTENSITY OF VERTICALLY PROPAGATING MOUNTAIN WAVES OVER THE ALPS

by

Joseph D. Coughlin

March 2005

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13. ABSTRACT (maximum 200 words)

Vertically propagating waves (VPWs) generated by prominent mountain ridges are a severe hazard to military aircraft operations. Properly forecasting the initiation and duration of such a phenomenon is critical, yet quite often missed by turbulence forecasters. A primary reason for poor forecast skill is vague VPW forecasting guidelines at the Air Force operational centers, focusing a majority of attention on the less severe, more common trapped lee wave response. The United States Air Forces in Europe Operational Weather Squadron (USAFE OWS) has requested a tool to aid in improving forecast ability of VPW events.
Satellite analysis from October 2003 through March 2004 indicated an occurrence of six major VPW events to the lee of the Alps. Actual verification of turbulence in each VPW was unavailable due to the minimal pilot report (PIREP) database kept for military flights over Europe, therefore, a subjective assessment of turbulent conditions was determined depending on the resulting cloud signature. Using NCEP GFS model analysis and upstream upper air soundings during these events, an average synoptic condition and critical weather parameters were created.
These developed tools were then tested from October 2004 through March 2005 to prove their reliability. In a limited data set these tools identified all VPW events, with only a 25% false alarm rate. This is compared to a 6% forecast ability with 0% false alarm rate determined during the 2003-2004 winter season by USAFE OWS forecasters. These new rules should be valuable in that they will provide a much needed capability for synoptic scale turbulence forecasters to better determine hazardous aviation conditions associated with VPWs.

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FORECASTING THE ONSET AND INTENSITY OF VERTICALLY PROPAGATING MOUNTAIN WAVES OVER THE ALPS

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Vertically propagating waves (VPWs) generated by prominent mountain ridges are a severe hazard to military aircraft operations. Properly forecasting the initiation and duration of such a phenomenon is critical, yet quite often missed by turbulence forecasters. A primary reason for poor forecast skill is vague VPW forecasting guidelines at the Air Force operational centers, focusing a majority of attention on the less severe, more common trapped lee wave response. The United States Air Forces in Europe Operational Weather Squadron (USAFE OWS) has requested a tool to aid in improving forecast ability of VPW events.

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I. INTRODUCTION

A. MOTIVATION

In the United States Air Force, turbulence forecasting is primarily being accomplished by relying on synoptic-scale guidance. Basic flow charts and rules of thumb about wind speed and terrain roughness are used to help the forecaster in determining the turbulence intensity and general alpine location. This form of surface-based mechanical turbulence is typically widespread, yet rarely of severe intensity. However, on much less frequent occasions, the atmosphere and a mountain range can induce gravity waves above and downstream of mountain ranges, that can lead to mountain-wave turbulence. One form of these mountain waves are vertically propagating waves (VPWs). Much like that of an ocean wave, if a VPW breaks the result is severe or even extreme turbulence, thus very hazardous to aircraft. Although infrequent in occurrence, forecasting these VPW events is imperative so that the aircrew can plan accordingly.

B. PROBLEM STATEMENT

The United States Air Forces Europe Operational Weather Squadron (USAFE OWS) hub has requested a tool to aid in forecasting the onset, intensity and duration of VPWs. Satellite analysis has shown that various terrain within the USAFE OWS area of responsibility (AOR) have produced significant VPW events (Figure 1).

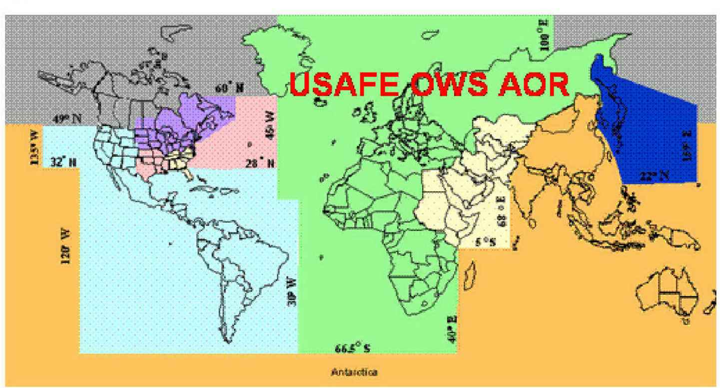

Figure 1. Global view of OWS AORs. The USAFE OWS AOR is highlighted in green and covers nearly all of Russia, Europe and Africa.

High aircraft trafficability, numerous US air bases and continual global reaching operations make forecasting these events all the more important. As a result USAFE OWS personnel producing Flight Hazard (Figure 2) and Mission Execution Forecasts (tailored individual aircraft route forecasts) must be able to provide aircrews with detailed information regarding the coverage and severity of mountain wave turbulence.

The tool currently used to forecast mountain waves by USAFE OWS personnel is the AFWA TN-98/002, *Meteorological Techniques*, which outlines various rules-of-thumb for forecasting mountain wave turbulence. The problem with this tool, however, is that these rules focus on the atmospheric parameters conducive to exciting horizontally propagating waves, disregarding forecast rules for VPWs (Appendix A).

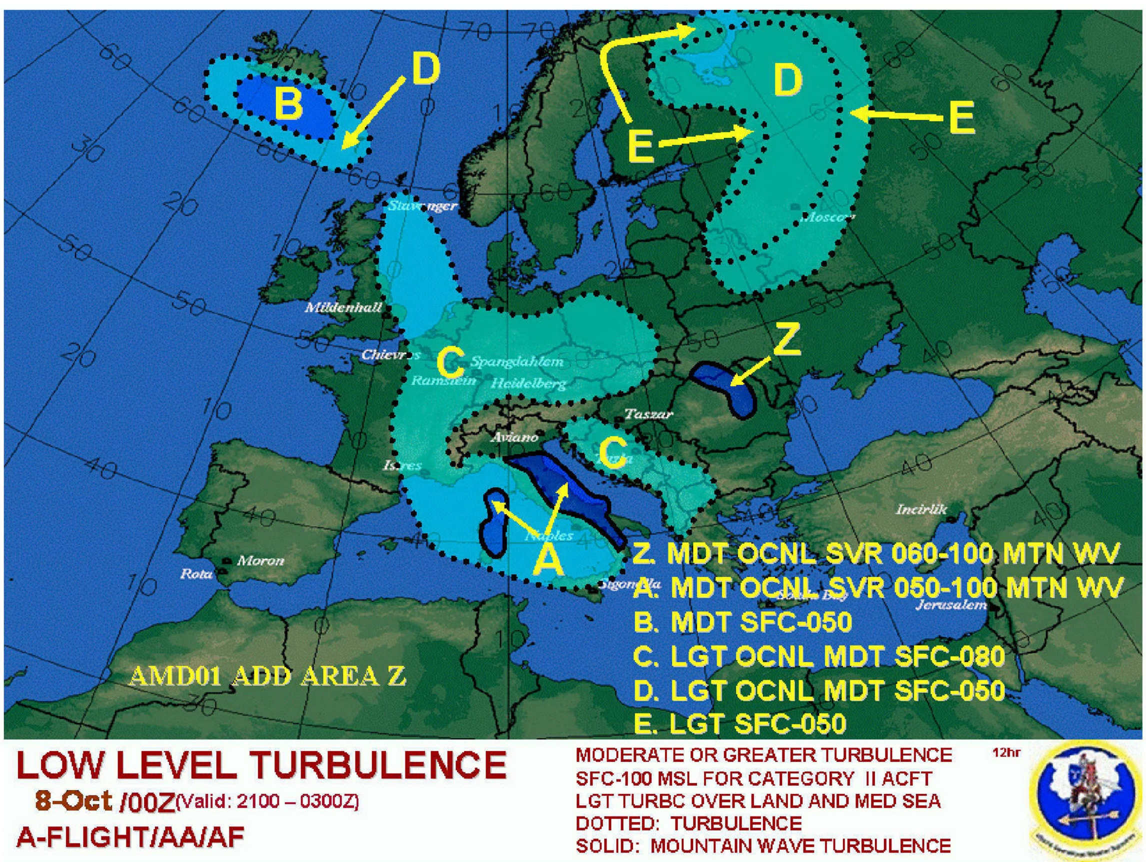

Figure 2. USAFE OWS Six Hour Low Level Turbulence Forecast Chart. This same background map is used on all European synoptic level charts.

C. REGIONAL SUMMARY

Of particular interest in this study are the Alps. This east-west oriented mountain range extends for over 700km from Eastern Austria, across Northern Italy, Switzerland and into Southeastern France. The Alps rise 2000-3000m above the surrounding Bavarian plains to the north and the Po River Valley to the south (Figure 3).

Also of significance is the high military trafficability around the Alps. Ramstein Air Base (AB), Germany, is located approximately 250km north of the base of the Alps and is the USAFE hub for cargo/tanker transport as well as medical evacuation. Ramstein AB is the primary staging location for most aircraft transiting from CONUS bases to the Balkans/Middle East and vice versa. Primary flight routes take these aircraft from Ramstein AB, southeast, over Austria and Italy, to forward deployed units in Bosnia, Kosovo, Turkey, Saudi Arabia, Iraq, Afghanistan, etc. Depending on the aircraft (fixed wing or helicopter), common flight levels can be anywhere from 500 feet up to 40,000 feet and beyond.

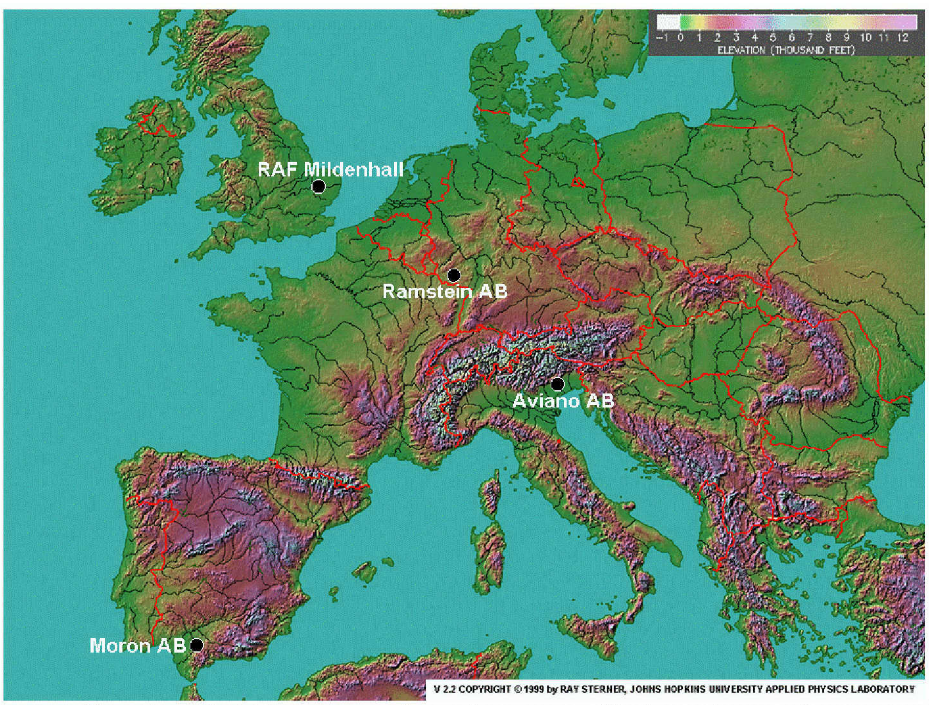

Figure 3. Continental European terrain map with locations of principal United States Air Force (USAF) bases. (After Sterner, 1999)

Another high impact location is Aviano AB, Italy. This base is located at the southern foot of the Alps in Northeastern Italy. Primarily a base with fighter aircraft, Aviano AB continually conducts missions throughout the former Yugoslavia. Thus, numerous flight routes out of both Aviano AB and Ramstein AB transit directly over and downstream (if there is a northerly wind component in the low-mid levels) of the Central and Eastern Alps, putting them at enhanced risk of encountering a VPW event.

D. FORECASTER OVERVIEW

Although there is considerable theoretical understanding of VPWs, operationally these events are infrequently forecast before the event onset (positive lead-time forecast), especially in the USAFE OWS AOR. Historically, VPWs are a challenging forecast parameter. One reason for this is there is rarely any observational data to verify this mesoscale to microscale phenomenon. Another is that the military forecaster responsible for predicting VPW events also has to forecast for all the various other scenarios that excite turbulent flow as well (thunderstorms, fronts, frictional effects, jet streams, etc). The primary European forecast area of concern is over twice the size of the continental United States, extending from about 30°W to 50°E Latitude (Lat) and from 30°N to 70°N Longitude (Lon). The forecast is then broken into six hour increments out to 36 hours as well into a low level chart (surface to 10,000ft above mean sea level) and upper level chart (>10,000ft above mean sea level), as can be seen in Figure 2.

Forecasting synoptic scale turbulence is only one of several weather hazards that the USAFE OWS hazards forecaster is responsible for. Along with low-level and upper-level turbulence, the hazards forecaster also provides similar forecasts for thunderstorms, warning level surface winds, icing and heavy precipitation. All of these products need to be accomplished during an eight hour shift while also METWATCHING (meteorological watching) the valid charts that had already been posted by the previous shift hazards forecaster. METWATCHING is done so as to be sure that other meteorologists and aviators

are looking at reliable forecasts that are meteorologically in category as required by Air Force Manuals 15-125 and 15-129. In the grand scheme, only a small portion of the hazards forecasters' time is dedicated to turbulence forecasting and an even smaller amount of that time is focused on mountain wave forecasting.

E. RESEARCH OBJECTIVES

On top of the substantial and varied workload, vague VPW forecasting guidelines at both the Air Force and USAFE OWS level as well as infrequent occurrences are likely to blame for a large forecasting error. Subsequently, aviators, who are briefed one to two hours prior to take-off, may be unknowingly put at risk for possibly severe to extreme turbulence when sortying (transiting) downstream of various mountain ranges susceptible to VPW development. Therefore, development of mountain range specific rules of thumb, in-depth event analysis training and basic, reliable model product tools are critical in order to develop the turbulence forecast, thus allowing the forecaster to provide a more accurate and timely product for aircrews without sacrificing precious time that also needs to go towards numerous other forecasting tasks.

The specific goals of this research are to:

1. Recognize signatures in the synoptic scale observed and model data that resulted in VPW development.
2. Develop a basic VPW forecasting tool that takes advantage of products the hazards forecaster routinely uses so as to not put excessive time constraints on other forecast products.
3. Provide a statistical analysis of location and frequency of VPW events throughout Europe.

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II. BACKGROUND

Turbulence is created by abrupt, irregular movements of air that create sharp, quick updrafts and/or downdrafts acting to dissipate gradients of kinetic energy (Reymann *et al* 1998). This unexpected air movement can cause serious damage to aircraft and potentially injure aircrew members and passengers. Turbulent motions develop from two basic atmospheric conditions, thermal/buoyant conditions and mechanical mixing. Radiational heating of the earth's surface is the primary cause for the boundary layer to become unstable. This unstable, more buoyant air then rises irregularly as an updraft, commonly becoming a cumulo-form cloud with pronounced updrafts and downdrafts. Although mountains can be a prime location for differential heating and subsequent thermal turbulence, a wave response does not occur in this type of environment (as described below). The other basic form of turbulence, mechanical mixing or Clear Air Turbulence (CAT), develops due to buoyancy and gradients (shear) in horizontal and/or vertical winds. Shear is a result of pressure gradient differences, fronts, or terrain obstructions (Reymann *et al* 1998). A statically stable atmosphere is one cause for strong horizontal/vertical wind gradients and if a parcel is vertically displaced in a statically stable atmosphere it will oscillate it in a wavelike motion. These oscillations, known as gravity waves, are disturbances in the atmosphere propagated by the force of buoyancy (Wurtele *et al,* 1993) and if break, can become extremely turbulent.

A. MOUNTAIN WAVES

Mountain waves are a form of internal gravity wave, where the wave disturbance is forced by a terrain feature. This disturbance occurs when the mean atmospheric flow encounters mountainous terrain and instead of being able to continue on its present course, it is forced vertically, transporting momentum and potential energy with it. Once displaced, this air can respond in several ways, primarily depending on the stability of the surrounding atmosphere

and the general shape, height and width of the mountain range. In an unstable environment, the displaced air is warmer and less dense than its surroundings and will continue to rise until it reaches thermal equilibrium. Once thermal equilibrium is reached, this displaced air will follow the environmental flow, which has minimal vertical motion. Thus an unstable environment is not conducive to wave propagation. If the environment is stable, the displaced air becomes colder and denser than its surroundings. The rate of ascent then slows and ultimately reverses directions so that it may reach thermal equilibrium. As the air descends it gains kinetic energy, thus, once reaching thermal equilibrium the air is not able to stop. It continues to descend, warming dry adiabatically, becoming warmer than its surroundings. This warmer, more buoyant air, slowly stops descending and begins to ascend back to its equilibrium level. This oscillating process continues until kinetic energy dissipates, damping the amplitude of the wave (Hooke 1986).

There are many different turbulence characteristics; therefore, it is often difficult for a forecaster to determine the type, intensity and duration of turbulent flow at multiple levels in the atmosphere. However, it is critical to accurately diagnose the atmospheric conditions and understand the small variations that can change laminar flow into turbulent flow.

B. TYPES OF MOUNTAIN INDUCED WAVES

Under specific atmospheric conditions, wind flowing across a mountain barrier can be forced to oscillate in an up and down motion above and downwind of the barrier. This is known as a mountain wave. There are two basic types of turbulence inducing mountain waves.

1. Trapped Lee Waves

Trapped lee waves are waves that propagate horizontally due to strong vertical wind shear or large stability changes just above ridge top level (known as a wave duct), either of which can act as a vertical propagation barrier. This wave duct interface allows wave energy to oscillate vertically below it; however, there

is exponential energy decay above (known as an evanescent wave). An inversion just above ridge top level with less stable stratification above is the typical trapped lee wave response scenario. Cloud bands that develop as a result of a trapped lee wave response have equidistant horizontal spacing as they oscillate and are parallel to that of the ridge axis that excited this oscillation (Figure 4). If the atmospheric conditions are favorable these cloud bands can extend dozens of times for hundreds of kilometers.

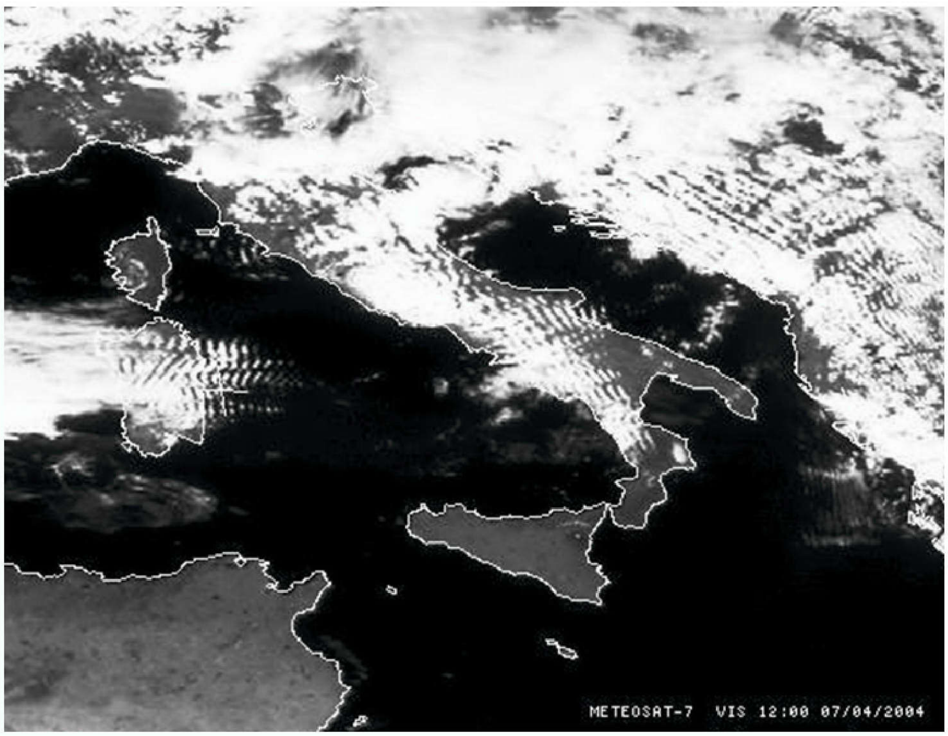

Figure 4. METEOSAT-7 visible image, 1200 UTC 07 April 2004. Trapped lee wave response downstream of mountain ranges in Sardinia, Italy and the Balkans. Note multiple wave crests at evenly spaced intervals.

Trapped lee waves are very common and significant effects to aircraft can be felt even downstream of hills with as little as 300-500m elevation gain above the background elevation (Queney *et al* 1960). Turbulence associated with trapped waves can be moderate to severe, especially in a rotor zone (Figure 5). However, the flow associated with trapped waves is thought to be primarily laminar (especially above ridge top level) due to the stunted vertical propagation. Therefore, turbulence is relatively nominal, especially for smaller and narrow mountains.

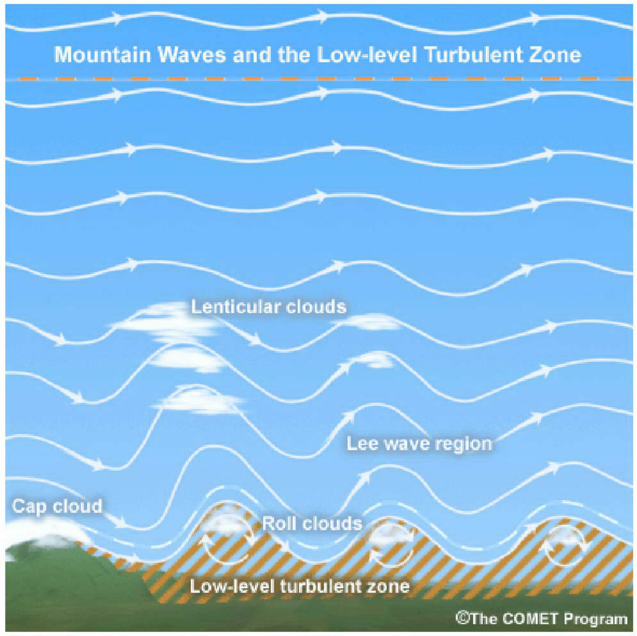

Figure 5. Streamline flow in a trapped lee wave response (From UCAR Mountain waves and downslope winds, 2005).

Trapped lee wave events are easily identified in higher resolution infrared and visible imagery by their narrow cloud features at the crest of the wave and dry/cloud free region at the wave base, with little to no visible propagation for the duration of the event on the satellite imagery. However, if the atmosphere has little moisture, clouds will not form at the wave crest and only high resolution water vapor imagery may be able to show this feature due to moisture variances from upward (moistening) and downward (drying) motions. In rare instances trapped lee waves are also observed due to aerosols. Because of their short wavelengths (3-15km), lower resolution imagery is typically not able to distinguish each individual wave, thus many times the synoptician can not identify the wave signature unless high resolution imagery is available.

2. Vertically Propagating Waves (VPWs)

As one might expect, VPWs are waves that propagate vertically. Uniform stability and minimal background vertical wind shear allows for these waves to extend to great altitudes, thus disturbing flow in the troposphere and stratosphere. Unlike trapped lee waves, which have multiple cloud crests, VPWs almost always have one wave crest (Figure 6) with some less severe events

having a second or third wave crest (Figure 7) of lesser vertical prominence (Durran 1986). A large cloud shield, almost always present, develops just downstream and sharply parallel to the axis of the mountain barrier. This cloud shield remains quasi-stationary (especially the leading edge) for the duration of the event and can have IR temps of -40° to -60° Celsius. Because VPWs are just a single wave, it is difficult to determine their exact wavelength; however, VPWs generally have wavelengths 30km or greater (Durran 1986). Unlike trapped wave responses, VPWs have a longer wavelength response that is easily discernable on both high resolution and low resolution imagery. Typically, it is larger mountain ranges like the Alps, Pyrenees, Rockies and Sierra Nevada that excite VPWs. Much like that of an ocean wave, the greater the amplitude of the wave the more likely the wave will break, thus causing severe to extreme turbulence. The large amplitude response of a VPW, thus, has a higher propensity to break than do trapped lee waves.

As seen by the satellite image in Figure 8, a Foehn gap (or Chinook Wall) is common between the mountain ridge axis and the leading edge of the cloud shield. This gap of clear air is on the order of several kilometers wide and occurs as air forced over the mountain descends and compresses rapidly thus warming dry adiabatically, evaporating any cloud droplets or ice crystals that it had as it crested the mountain. Reymann *et al* (1998) states that the non-existence of a Foehn gap indicates less turbulent airflow due to weaker vertical motions. However, there may be times when a Foehn gap is obscured by upper level clouds or cannot be determined remotely due to poor satellite resolution and/or inability to accurately locate the ridge axis. Luckily, in Figure 8 a weak upslope flow in France brought cloud cover to the northern slopes of the Pyrenees, thus a Foehn gap is easily distinguishable between the upslope stratus and the downstream VPW response. The Foehn gap can exist in both VPW and trapped lee wave events. However, the Foehn gap only indicates that descent has occurred and not necessarily due to a mountain wave.

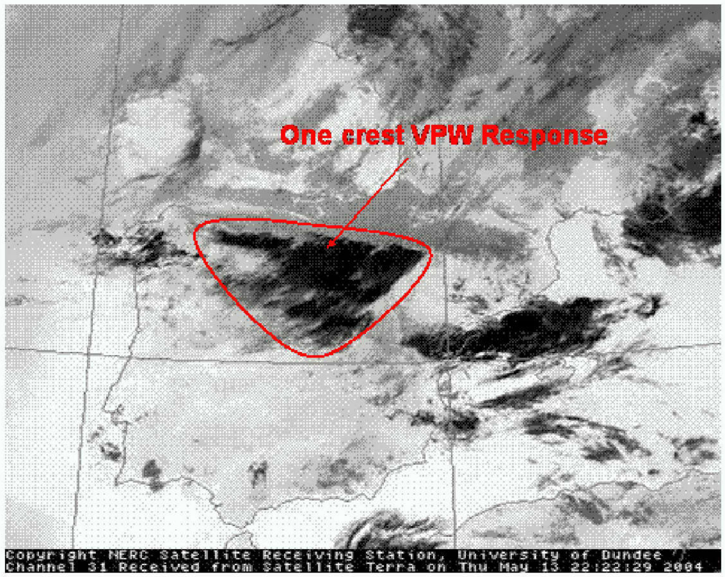

Figure 6. MODIS Terra Ch31 infrared image, 2222z 13 May 2004. Example of a one crest VPW just downstream of the Pyrenees. This inverse color (dark represents cold cloud tops) image depicts mid and upper level clouds over France, indicating a northeasterly flow, nearly perpendicular to the primary axis of the Pyrenees.

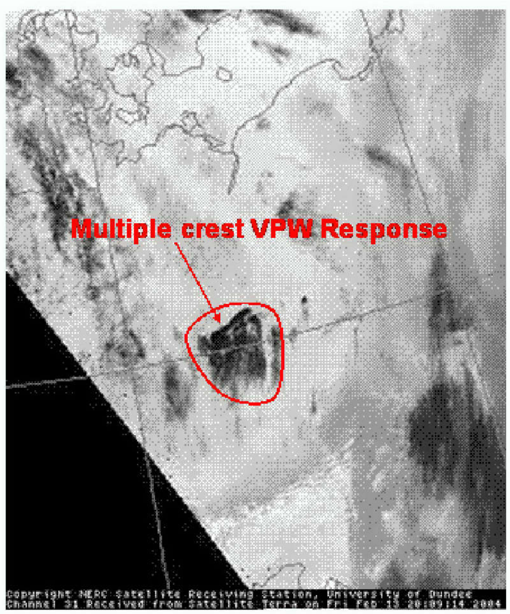

Figure 7. MODIS Terra Ch31 infrared image, 2009z 13 February 2004. Example of a multiple crest VPW just downstream of the Erzgebirge Range along the Germany/Czech Republic border. This inverse color image shows a strong initial wave crest reaching well into the upper troposphere (very bright cloud top response compared to much lighter trapped wave response over the Eastern Alps). However, possibly two troughs are evident further downstream, indicating a weaker than normal VPW event.

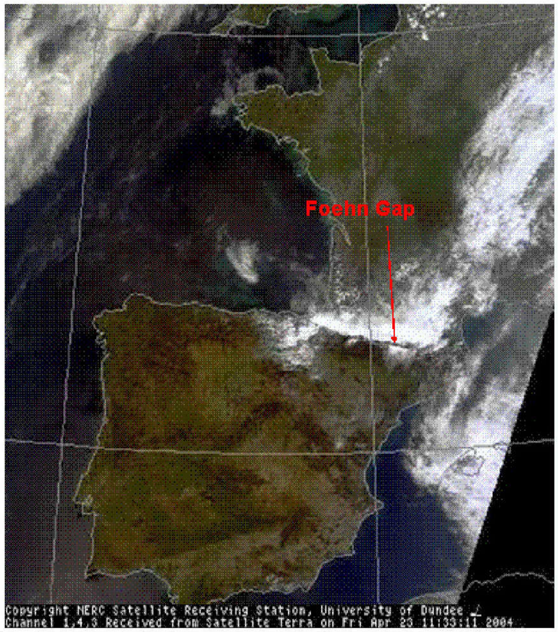

Figure 8. MODIS Terra visible composite image, 1133z 23 April 2004. Clear example of a Foehn gap located between the stratus on the northern slope of the Pyrenees and VPW over the southern slope of the Pyrenees.

C. CHARACTERISTICS OF VPWS

VPWs have been observed for several decades across the entire globe. Looking at satellite imagery, it is clear that VPWs develop on the leeside of large-scale mountain ranges like the Rockies. However, they can also develop to the lee of much smaller, isolated terrain like the Schwarzwald/Black Forest of Germany (terrain rising about 1000m above the Rhine River valley and approximately 50km wide). There are two basic factors that affect the development and severity of VPWs (Whiteman 2000):

Atmospheric conditions:

- Wind speed and direction of air approaching the underlying terrain
- Stability of air approaching the underlying terrain

Terrain characteristics:

- Barrier width (along flow distance)
- Barrier length (normal flow distance)
- Barrier height (above background elevation)
- Barrier profile/shape

1. Atmospheric Conditions

Unlike trapped lee waves, which have been thoroughly studied for over 80 years, the basic flow to excite VPWs has only begun to be understood in the last three decades. General theory and observational analysis tells us that VPWs, much like trapped lee waves, occur when upstream synoptic-scale flow becomes perpendicular to the mountain ridge axis. However, it has been often observed that many mountain ranges that have produced VPWs also produce trapped lee waves responses. Therefore, with terrain characteristics unable to be the sole explanation for exciting two different types of wave turbulence, some varying atmospheric condition must be the answer as to why a parcel can propagate vertically to great lengths one day and oscillate about a level in the lower troposphere another day. This varying condition is stability. One measure of stability in a layer is the Brunt Väisälä Frequency (*N*),

$$N = \sqrt{\left(\frac{g}{\theta_0}\right)\left(\frac{d\theta_0}{dz}\right)} \qquad (2.1)$$

where *N* is clearly dependent on gravity and temperature and increases with greater static stability. Another stability term, the Scorer Parameter $\left(\ell^2\right)$:

$$\ell^2 = \frac{N^2}{U^2} - \frac{1}{U}\frac{d^2U}{dz^2} \qquad (2.2)$$

is a measure of stability versus the vertical wind profile, where U is the wind speed perpendicular to the ridge axis (Scorer 1949). Due to the difficulty of a radiosonde to accurately measure the minute values of d^2U, a simplified approximation of the Scorer Parameter (ℓ),

$$\ell = \frac{N}{U} \qquad (2.3)$$

can be used (Durran 1986). Holding *N* constant with height, it is easy to see that a wind increase with height (typical for a standard atmosphere) causes a decrease in ℓ. As Scorer (1949) showed, a large decrease in ℓ is conducive for

a wave to become trapped. It was later found that a profile where ℓ remains nearly constant with height $(d\ell \approx 0)$ is favorable for VPW development (Durran 1986). Therefore, a profile with minimal vertical wind shear $(dU \approx 0)$ and minimal vertical gradient of *N* $(dN \approx 0)$ would be conducive for VPW development. However, it is possible to have a primary wave propagate vertically and to also have a trapped lee wave response.

a. Wind Flow

As mentioned earlier, near perpendicular flow at and just below ridge top level allows vertical displacement of the parcel, thus giving it the potential energy necessary to ascend the barrier. Just as important as the upstream direction, is the wind speed. Depending on the terrain characteristics, some minimum background low-level flow speed is needed for the air parcel to ascend over the mountain. If this minimum flow is not met then flow blocking occurs and some air flows around the mountain and does not generate VPWs (Figure 9a). If the minimum flow is met, then the parcel of air will be able to pass over the mountain and possibly generate a gravity wave (Figure 9b).

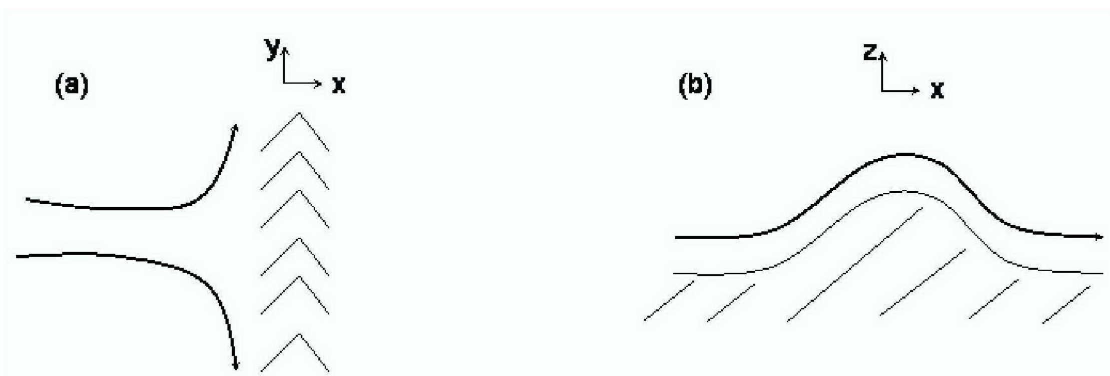

Figure 9. (a) Flow blocking due to terrain and/or light wind speed. (b) Flow not blocked, thus able to pass over terrain.

Minimum flow speed allowing a parcel to pass over terrain only indicates favorable flow in the low-levels. To excite a VPW, the entire column of air must be favorable by satisfying $d\ell \approx 0$. This is accomplished by having a wind profile with little change in speed or direction at and above the mountain (i.e., no jet max aloft). The general rule of thumb is that the mountain top wind

speed be less then 1.6 times the wind speed 2000 m above mountain top to allow vertical propagation (UCAR Mountain waves and downslope winds 2005).

b. Stability

As was mentioned previously, a stable atmosphere is required for a leeside oscillation to occur. Acting as a vertical barrier, the more stable the atmosphere is at ridge top level (larger *N*), the greater the wind speed must be to counteract this and penetrate upwards. It is well documented (Queney *et al* 1960) that an inversion above mountain top level is conducive for lee wave development associated with a wave duct. This inversion acts to generate a large value of ℓ in the lower troposphere beneath lower values of ℓ aloft. For a VPW, though, a ℓ value that is nearly constant with height is needed, so any type of inversion above mountain top level would be detrimental to the initiation of a VPW.

Certain atmospheric conditions, like a stable, cold dome of air banked up against the upstream slope of the terrain may behave as "effective topographic" enhancements (Whiteman 2000). This cold dome of air acts to widen and smooth the underlying terrain.

2. Terrain Characteristics

As mentioned above, the terrain width, length, height and profile play an integral part in determining if mountain waves will occur and if so, what type.

a. Terrain Width

From observational and theoretical analysis a wide mountain is most conducive for development of VPWs, although not too wide so that the Coriolis force and subsequent turning of the flow becomes important (Durran 1986). The Coriolis force becomes a factor when an event takes over twelve hours to develop. Optimum width can be anywhere from 50 to 200 km (Klemp and Lilly 1977). This large range is because a mountain is considered "wide" when the inverse of its half width (a^{-1}) >> ℓ. Dependent on N and U, ℓ is a continuously changing variable and an environmental condition that is favorable for one mountain range may not be for another, depending on the differing half widths.

b. Terrain Length

Although mountains of various terrain cross-flow scales can excite VPWs, it has been recognized observationally that all other parameters being considered equal, the longer the terrain length, the more favorable for VPW development. A simplistic explanation for this is that a when a flow encounters a lengthy mountain, the only place it can go is up and over. An isolated obstacle, though, only provides a small amount of blocking in the horizontal so undoubtedly some of the airstream is deflected horizontally.

c. Terrain Height

Terrain height can act to minimize or intensify VPW events in several ways. Physically, the higher the terrain is, the greater the vertical displacement. A parcel would have to travel much further vertically to attain thermal equilibrium, thus the greater the amplitude of the wave, which means more severe turbulence. However, it has been shown that any mountain in a statically stable flow, with a vertical rise of at least one kilometer, no matter how gentle the slope, can produce a VPW (Smith 1977). Dynamically, if the perpendicular flow is rather weak and the mountain is of substantial height, the kinetic energy required to pass over the mountain will be too large and the flow becomes blocked. Blocked flow means no displacement over the mountain top, thus no wave formation (Figure 9a). If the mountain is rather small, a parcel will easily ride over the mountain but will not have gained enough potential energy nor become cooler than its environment to begin an oscillation. It is when flow is partially blocked, that a parcel can crest a mountain and subsequently oscillate on the lee side. A proven way to determine if flow will be able to pass over the terrain and be able to oscillate once displaced, is to use the Froude Number (F_r), a ratio of kinetic energy (KE) to potential energy (PE),

$$F_r = \frac{U}{NH} \qquad (2.4)$$

where H is the height of the mountain. $F_r \ll 1$, indicates PE > KE, thus flow blocking. $F_r \gg 1$ means little to no flow blocking. However, when $F_r \approx 1$ (generally from 1 to 2) there is enough KE for the parcel to breach the top of the

mountain and enough PE for the parcel to accelerate downwards and begin the oscillation process. The closer F_r gets to 1, the more intense the VPW becomes (UCAR Mountain waves and downslope winds 2005).

d. Terrain Profile/Shape

Unless the mountain is a perfect volcanic cone, chances are the slope and/or elevation gain differ on the windward and leeward side. These irregularities cause the amount of KE needed to crest the mountain and the amount of resultant PE (once over the crest) to be different. These differences determine if a mountain range is more or less favorable for VPW development, and the possible intensity. Figure 10a shows upwind terrain at a much higher elevation than downwind, while Figure 10b has a reverse profile. With the same mountain height, a parcel reaching the top of each mountain would have the same amount of PE (environmental conditions being equal), however, the amount available PE is much higher in Figure 10a due to the possibility of greater atmospheric descent. This means that a mountain range with a large leeward relative height change (i.e., the Alps with northerly flow) can produce a more severe VPW event.

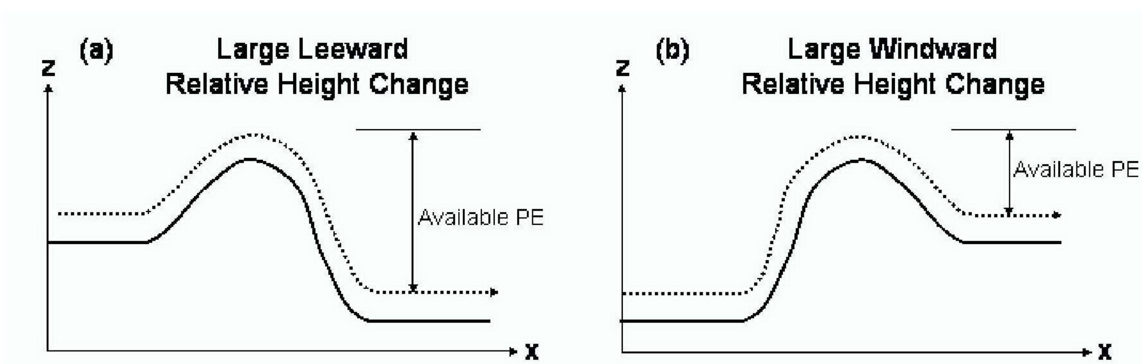

Figure 10. (a) Mountain range with a large leeward relative height change (i.e., Alps, Front Range of the Rockies). (b) Mountain range with a large windward relative height change (i.e., Sierra Nevada). With prevailing flow from left to right, greater leeside descent is able to occur in (a), thus making it more susceptible to more intense VPW events.

D. LIMITATIONS TO VPW UNDERSTANDING

Trapped lee waves have been observed and well studied for over 80 years. Their unique cloud signature is easily visible, even from a surface observation. Their typically laminar flow above mountain top (Figure 5) has made them a popular and well known phenomenon, especially for glider pilots. Understanding of VPWs, however, has taken much longer. Although unique, the VPWs cloud signature is only accurately observed with satellite imagery or PIREPs, due to its much larger scale/wavelength response and higher altitude effects. Satellite imagery and frequent high-altitude flights only routinely came to fruition in the 1950's. Even so, few PIREPs are available for these rare yet destructive events. With minimal observational data, it is difficult to determine if wave breaking is occurring during one VPW event, but not another. Because of this, only subjective analysis as to turbulence associated with each VPW can be done.

Unlike the theoretical typical bell shaped mountain, most mountains consist of abrupt changes in slope and/or multiple ridges. Varying surface topography creates oscillations, which can be either amplified or decayed, depending on whether the wavelength relative to the mean flow is similar to, less than or greater than the harmonic wavelength of the terrain (Holton 1992). These varying surfaces are quite difficult to model and study in a research environment, so it is imperative that observational studies be done on individual mountain ranges to better understand the range of atmospheric parameters that excite VPWs. Save numerous studies in the Colorado Rockies and Sierra Nevada, little surface and upper air observational analysis has been done on VPWs. Thus, because of terrain differences between every mountain range, only very generalized rules of thumb can be utilized in the prediction of VPWs.

Just like a trapped wave response, theory tells us that VPW formation, intensity and duration is quite sensitive to the background atmospheric flow. Observational studies like the Sierra Wave Project throughout the 1950's have continually shown this to be true (Queney *et al* 1960). These studies, though,

have only dealt with trapped lee wave responses. Although numerous studies examine the theory of VPWs, few have documented the general synoptic flow and ranges of flow that are favorable for the development of VPWs for specific mountain ranges.

E. RESEARCH FOCUS

Satellite observations indicate that there are numerous mountain ranges that produce VPWs within the USAFE OWS AOR. With all the events, flow directions and varying terrain characteristics, it was necessary to focus on just one range so as to be able to develop a complete, concise dataset on conditions that excite VPWs in that region. If this was not done, only a generalized tool would be available and little benefit would result. Because of their high military trafficability and numerous VPW events, the Alps were an easy decision as the range of interest.

The primary focus in this study is to use the data extracted from VPW events downstream of the Alps to develop a forecaster rule-of-thumb tool which will improve forecast skill by extending the use of synoptic scale information through a clear application of VPW theory. The reason behind providing tools on the synoptic scale is twofold; forecaster ease of use with routine products and potential mesoscale model limitations in direct predictions of VPWs.

As mentioned previously, the operational forecasters that will be using the results of this study are synoptic scale hazards forecasters. They produce forecast charts out to 36 hours, covering vast areas of the European continent. Turbulence is only one of five hazards that this forecaster must focus on. For this reason alone, a tool that requires little extra time in their busy schedule is a must. If the tool provided to them is labor intensive, other forecasts will undoubtedly suffer.

The model of choice for these forecasters is the United Kingdom Meteorological Office (UKMO) Global Model. The UKMO is the interactive model on each individual forecaster's HORACE (a UNIX based Hewlett Packard work

station) terminal. The UKMO provides a full suite of atmospheric variables out to 144 hours and using the HORACE, it is very easy for the user to manipulate variables. Using a global scale model and its subsequent graphical output, allows the forecaster to produce a complete synoptic scale product without having to focus in on several high resolution mesoscale model windows. The hazards forecasters' job at the USAFE OWS hub is to produce a forecast product on the synoptic scale, which can and may be tailored by the tactical weather forecaster who is focused on mesoscale processes. On that note, it must be restated that VPWs are very sensitive to the background synoptic scale flow. A mesoscale model may not be as skillful in the synoptic-scale depiction as a global model because of a number of issues including limitations due to the lateral boundary conditions.

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III. DATA ANALYSIS

During the course of the research on this thesis, nearly every trapped lee wave and VPW event over continental Europe from October 2003 through March 2004 was recorded. Due to data limitations, the region of analysis by no means covers a majority of the territory for which the USAFE OWS is responsible (Figure 1). However, the area of study includes a vast majority of the European hazard forecast chart (Figure 2) area and only excludes two USAF bases, Lajes Field, Azores, Portugal and Incirlik AB, Turkey.

A. VPW IDENTIFICATION

Although numerous in coverage, surface observations did very little to indicate VPW events. Also, military and civilian PIREPs attained from the Air Force Combat Climatology Center (AFCCC) were meager and quite suspect due to their multiple encoding errors. Because of this, VPW identification had to be accomplished solely by satellite analysis. Defining a VPW in this fairly restrictive sense had to be done because of limited observational and model data. Satellite analysis consisted of first, becoming very familiar with the terrain location, size and axis. A standard topographic contoured atlas was of great use in the familiarization as well as subsequent referrals throughout the study. Without this knowledge, analysis would have been nearly impossible. Using various images from published studies (Durran 1986) and workshops (UCAR Mountain waves and downslope winds 2005), as well as previous USAFE OWS forecasting experience, a general idea of the VPW signature (Figure 6) became clear. Typical signatures included,

- Sharp cloud/thermal contrast between ridge axis and leading edge of cloud downstream of ridge. IR contrast can be 20°C-40°C or more
- Large, stationary, single wave cloud shield. Multiple crests indicate trapping, thus weaker intensity
- No convection in the area. This indicates atmospheric instability. Remember, a more stable environment is needed.

1. MODIS Imagery Analysis

Initial analysis was done using archived polar orbiting MODIS Aqua and MODIS Terra satellite imagery. This approximately 1 km resolution imagery archive was available at http://www.sat.dundee.ac.uk/auth.html, the website of the National Environment Research Council Satellite Receiving Station, Dundee University, Scotland. MODIS channels 1, 2, 3, 4, 5, 6, 7, 22, 25, 28, 30, 31 and a visible composite image were typically available for daytime viewing analysis, while nighttime analysis channels available were 22, 25, 28, 30 and 31. There were roughly 8-15 satellite passes to view per day, covering a geographic area from 25°W-30°E Lat, and 30°N-70°N Lon. With 2 satellites in orbit, this meant that every location in continental Europe was guaranteed at least 3 to 5 passes per day. Numerous channels of every satellite pass from October 2003 through March 2004 were analyzed for both VPW and trapped lee wave responses. With such high resolution, even the shortest wavelength responses were easily distinguishable on MODIS. Every potential VPW and trapped lee wave event was recorded by image time, date and terrain location.

Of note, the channel that gave the best VPW identification was the long wave infrared (IR) channel 31 (10.780-11.280μm). This color inverted IR channel (Figure 6) worked well both night and day and gave an unmistakable thermal contrast between the relatively warm, dry air at surface level and the very cold downstream cirrus shield response.

Because trapped lee wave responses may not have enough vertical propagation to generate condensation and cloud formation, the water vapor channel 28 (7.175-7.475μm) was used to identify moisture differences, not necessarily cloud top temperature differences. In doing so, not a single VPW event using the water vapor channel was identified, that wasn't already clearly visible on the long wave IR channel. This most likely means that if a VPW exists it will have a cloud signature.

2. METEOSAT Imagery Analysis

After analyzing a years worth of high resolution MODIS satellite data and building a dataset of over 500 possible VPW and trapped wave events, it was obvious that the research needed to be focused on just the VPW events (more severe event of greater concern to aircrews) over a specific mountain range (the Alps), thus reducing the primary dataset over 30 fold. More specifically, a northwesterly flow over the Eastern and Central Alps sparking VPWs over Italy and Slovenia was the main concern due to highest military trafficability over and south of Austria (Switzerland has a military no fly zone and there are relatively few routes taking US military aircraft over the French Alps). However, because VPWs are not the easiest event to detect with just a single satellite image, an archived satellite loop would be of ultimate importance in verifying the formation and duration of this stationary phenomenon. Thankfully, the USAFE OWS kept an archive of low resolution (8 km) METEOSAT IR satellite loops. This low resolution image would have been nearly useless for the short wavelength response of the trapped lee wave. This IR loop is more than adequate, though, for the determination of the very long wavelength response of the VPW.

The USAFE OWS archive had three 8-hour METEOSAT loops per day. Although some of these loops were unavailable due to file corruption, a vast majority of the loops were operable and every available loop for that eight month period was reviewed to determine if a VPW response did occur. Not only did the loop confirm and deny some of the probable VPW events (improper assessment with the MODIS was due to thunderstorms, jet streaks, etc. that had a sharp cloud edge near the base of the Alps), it also identified other events that may have occurred during times when the polar orbiter was not overhead or was difficult to distinguish with just a single image. Overall, the VPW responses were much easier to identify with the low resolution METEOSAT loop than with the high resolution polar orbiter imagery.

B. UPPER AIR OBSERVATION ANALYSIS OF VPWS

Upon completion of the satellite analysis, a data set of VPW events occurring south of the Central and Eastern Alps was developed. The dates and valid times of each event are listed in Table 1.

Event #	Year	Month	Start Date/Time	End Date/Time	Event Duration
			(DD/HHz)	(DD/HHz)	HH
1	2003	Oct	11/05z	11/09z	4
2	2003	Nov	18/17z	19/22z	29
3	2004	Feb	03/00z	06/11z	83
4	2004	Feb	13/12z	15/05z	41
5	2004	Mar	03/01z	03/12z	11
6	2004	Mar	03/19z	04/09z	14

Table 1. VPW events south of the Central and Eastern Alps. Dates of analysis were 01 Oct 2003 thru 31 March 2004.

The most basic forecast guidance on any wave perturbation is with the general wind flow. According to Queney *et al* (1960) wave propagation was possible when flow was within 30° of perpendicular to the ridge axis, wind speeds at ridge top level were at least $7ms^{-1}$ to $15ms^{-1}$ (approximately 15-30kt) and winds increased significantly with height. These rules were set in forecasting trapped lee waves, therefore, are not entirely accurate for VPW development. However, they provided a good starting point for this research on VPWs.

In order to initiate a VPW to the south-southeast, the background flow is from the northwest. Consequently, it was imperative to find an upper air station just north of the base of the Central Alps, unobstructed by perturbed flow over the mountains. Using the University of Wyoming, Department of Atmospheric Science webpage, http://weather.uwyo.edu/upperair/sounding.html, archived European upper air observations were available from the Munich-Oberschlssheim station (10868). At a Lat/Lon of 48.25°N, 11.55°E and elevation of 489m this station is located about 50 km north of the base of the Bavarian Alps, an excellent upstream station for this study.

The next step was to obtain every upper air observation from the Munich station taken just before and during the valid time of the six VPW events. The Munich station does a full upper air sounding every 12 hours so there were 14 observations available during the specified times (Table 2). Of primary interest was the 700 hPa wind speed and direction (rough mountain top level for Central/Eastern Alps), 500 hPa wind speed and direction (2000m above mountain top level) and the jet max speed (further determination of wind speed increase or decrease with height). With these 14 data points, a range of 700 hPa, 500 hPa and jet max speed as well as 700 hPa and 500 hPa direction were derived. These ranges gave a rough outline of what atmospheric flow conditions are necessary for the Central/Eastern Alps to develop a VPW. This rough outline fit the theoretical profile of near perpendicular flow, and moderate flow at ridge top level minimally increasing with height.

Munich Upper Air Observations during VPW's

Event #	Year	Month	Date/Time DD/HHz	700mb Dir	700mb Speed kt	500mb Dir	500mb Speed kt	Jet Max Speed kt
1	2003	Oct	11/00z	290	27	300	47	54
2	2003	Nov	19/00z	315	17	330	31	51
3	2004	Feb	03/00z	305	35	325	51	74
3	2004	Feb	03/12z	315	25	340	39	62
3	2004	Feb	04/00z	300	31	315	33	47
3	2004	Feb	04/12z	295	21	310	35	60
3	2004	Feb	05/00z	285	31	295	37	62
3	2004	Feb	05/12z	290	27	295	37	66
3	2004	Feb	06/00z	275	41	295	64	82
4	2004	Feb	14/00z	355	21	355	31	54
4	2004	Feb	14/12z	360	17	365	25	47
4	2004	Feb	15/00z	335	21	340	33	49
5	2004	Mar	03/00z	315	21	365	31	39
6	2004	Mar	04/00z	330	27	345	49	70
			Range	275-360	17-41	295-005	25-64	39-82
			Avg	311.8	25.9	326.8	38.8	58.4

Table 2. Upper air flow speeds and directions at Munich during VPW events.

C. UPPER AIR OBSERVATION ANALYSIS OF NON-VPWS

The general flow range of the Munich upper air obs (Table 2) that sparked VPWs downstream was then used in analyzing all Munich upper air obs from October 2003 through March 2004 to determine what other times fit this flow range. A total of 27 Munich obs met the flow criteria. The only apparent difference was that this data set contained obs where no VPW event was detected. These 27 obs are characterized as non-VPW obs (Table 3).

Munich Upper Air Observations during non-VPW's								
Event #	Year	Month	Date/Time	700mb Dir	700mb Speed	500mb Dir	500mb Speed	Jet Max Speed
			DD/HHz		kt		kt	kt
1	2003	Oct	08/00z	300	21	350	25	54
2	2003	Oct	10/00z	310	27	345	54	72
3	2003	Oct	10/12z	280	31	310	35	45
4	2003	Oct	11/12z	285	25	310	43	60
5	2003	Oct	12/00z	290	29	300	29	58
6	2003	Oct	12/12z	330	17	330	41	43
7	2003	Nov	04/12z	295	23	345	39	60
8	2003	Nov	13/12z	310	31	355	27	47
9	2003	Nov	17/12z	305	21	300	31	52
10	2003	Nov	18/00z	305	33	305	49	70
11	2003	Nov	18/12z	305	27	340	33	82
12	2003	Dec	06/12z	300	39	305	37	47
13	2003	Dec	15/12z	320	33	320	56	74
14	2003	Dec	23/00z	320	21	345	35	56
15	2003	Dec	26/12z	275	21	305	25	41
16	2004	Jan	07/00z	310	27	305	37	82
17	2004	Jan	08/00z	330	17	345	43	64
18	2004	Jan	10/00z	295	41	300	47	70
19	2004	Jan	15/12z	298	28	315	41	60
20	2004	Jan	16/00z	280	17	330	45	78
21	2004	Jan	22/12z	350	21	355	62	78
22	2004	Feb	10/00z	310	31	330	58	74
23	2004	Feb	10/12z	325	25	345	45	72
24	2004	Feb	15/12z	360	21	345	37	43
25	2004	Mar	03/12z	325	23	350	35	82
26	2004	Mar	04/12z	320	23	340	47	68
27	2004	Mar	05/00z	335	25	365	39	47
			Range	275-360	17-41	300-005	25-62	41-82
			Avg	309.9	25.9	329.3	40.6	62.2

Table 3. Upper air flow speeds and directions at Munich during non-VPW events that fell in the range specified in Table 2.

Presuming that this flow range is exactly correct in predicting VPW events and that all VPW events have a discernable signature on IR imagery, using just this flow range parameter as the forecasting tool would give a 100% prediction

rate (our ultimate forecasting goal), however, it would also give a 66% false alarm rate. That means for every event that is forecast properly, there are two forecasts that do not materialize into VPWs. This false alarm rate is much too high. With this amount of inaccuracy, it is obvious to see that wind flow is not the only significant atmospheric parameter in determining VPW development. Therefore, comparing the similarities and differences in stability and synoptic-scale pattern between these two sets of observations will give us additional critical information in the prediction of VPWs, hopefully reducing the false alarm rate while keeping event forecast accuracy very high.

D. USAFE OWS VPW FORECAST ABILITY

With a solid understanding from satellite analysis of when VPW events occurred over the Alps and an archived set of hazards turbulence forecasts from 01 October 2003 through 31 March 2004, a study of the USAFE OWS VPW forecast ability was possible. Each hazards forecast slideshow in the archive included seven 6-hr turbulence forecasts. Because of increasing model error with time, thus decline in forecaster accuracy, only the first three forecast slides (forecast going out to 18 hours) were reviewed. To make sure no false alarm forecasts were issued, every day of turbulence forecasts were inspected, not just the dates where VPWs were observed. Table 4 shows VPW observation vs. VPW forecast. As could be imagined, the overwhelming majority of forecasts were for no VPW and no VPW was observed (95% accuracy). However, that is not the alarming statistic. The forecaster's skill is measured when a VPW is observed. There were a total of 46 forecasts issued that were valid when a VPW was observed. Of those 46 forecasts, only two times did the USAFE OWS forecast them with a positive lead time (5% accuracy). The actual charts that are valid and METWATCHED to ensure quality are only those counted in Table 4a and 4b. 32 forecasts issued were valid when a VPW was observed during either the 00-06 hr or 06-12 hr period, of which only 2 turbulence forecasts correctly depicted any mention of a VPW event (6% accuracy). Of 30 missed forecasts that were required to be amended for being out of category due to

significant mountain wave turbulence, only four were. Not a single forecast for mountain wave turbulence over the Alps was issued for greater than six hours out, indicating a reactive forecasting unit rather than proactive. These statistics not only show a critical problem in forecasting accuracy but also in the lack of satellite analysis skills to detect a VPW response.

a)

00-06 hr low-level turb forecast		VPW Forecast by USAFE OWS	
		YES	NO
VPW Observed	YES	2	14
	NO	0	293

b)

06-12 hr low-level turb forecast		VPW Forecast by USAFE OWS	
		YES	NO
VPW Observed	YES	0	16
	NO	0	293

c)

12-18 hr low-level turb forecast		VPW Forecast by USAFE OWS	
		YES	NO
VPW Observed	YES	0	14
	NO	0	295

d)

Total 00-18 hr low-level turb forecasts		VPW Forecast by USAFE OWS	
		YES	NO
VPW Observed	YES	2	44
	NO	0	881

Table 4. VPW Observation vs. Forecast diagram for short term low-level turbulence forecasts from 01 October 2003 through 31 Mar 2004. Diagram a) 00-06 hrs, diagram b) 06-12 hrs, diagram c) 12-18 hrs, and diagram d) is a summation of diagrams a, b and c.

E. MODEL DATA

In order to gain an understanding of the average synoptic situation during VPW and non-VPW events, a much more advanced method of analysis had to be used rather than just viewing point-based upper air obs. The most basic and straightforward method was to take model 00-hr analysis data and examine it as an excellent approximation of the current state of the environment. Therefore, by using the 00-hr analysis, a much more accurate depiction of the actual conditions that excited VPWs was possible than if a long term or even short term forecast was used. From the model analysis, synoptic conditions that result in VPWs are depicted and can then be applied to model forecasts to determine VPW forecast skill. Due to model forecast error, a larger error in accurately determining the

conditions that developed VPWs would occur. This research was not intended to focus on model reliability nor help to provide a model of choice in forecasting VPWs, but rather to develop a robust association between synoptic patterns and VPW events.

The model of choice for the USAFE OWS forecaster is the Global UKMO, however, only a small portion of the full UKMO vertical suite (7 layers) was available to the NPS Meteorology Department. In studying vertical propagation it was critical to exploit a model with as many vertical layers as possible. Instead of analyzing this limited product that only slightly resembled the capabilities of the UKMO data available to the USAFE OWS forecaster, it was decided to use the National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) medium range forecasting model.

1. NCEP GFS

The GFS is a global spectra model that uses the sigma (terrain following) vertical coordinate system. The 00-hr analysis used in this research has a roughly 0.6° or 55km horizontal resolution as well as 64 vertical layers (UCAR Operational Models Matrix, 2005). However, only 23 levels on a 1° grid were available for this study. This model is run every six hours; however, because upper air data is available just twice a day, only the 00z and 12z analyses were utilized in this study. Using a UNIX based program called REGRID, the global model was truncated to a limited area and re-centered over roughly the same geographical area as in Figure 2. Another UNIX based program called AVERAGE was able to compute the average synoptic situation during VPW events. The results from the REGRID and AVERAGE programs were then displayed through a graphics program named VISUAL.

2. REGRID Process

The program REGRID is a FORTRAN program developed by Prof. Wendell Nuss that takes gridded model fields on any grid and interpolates them to a user specified grid. The method uses multiquadratic interpolation (Nuss and Titley 1994) where the interpolation to a specified point on the new grid is based on fitting the surrounding 36 grid points on the original grid. The approach is

applied horizontally level by level to produce a three dimensional data set on the desired grid. The method allows for model data on all types of map projections (Lambert Conformal, Latitude/Longitude, Mercator, etc) to be re-mapped to any other grid on a different map projection. This allows different models to be directly compared on the common grid.

3. AVERAGE Process

Average is a FORTRAN program written by Prof. Wendell Nuss that computes a list of gridded datasets and computes the mean and standard deviation of the specified field at individual grid points. The result is a composite grid of the field over the domain which can then be displayed.

4. VISUAL Program

The program VISUAL is a FORTRAN program developed by Prof. Wendell Nuss to display a wide variety of meteorological datasets. The program is based on NCAR Graphics and XGKS graphical software for plotting. The program allows a variety of computations to be performed on gridded dataset in addition to plotting the grids. Horizontal depictions, vertical cross sections and sounding displays of basic and computed parameters can be done and overlaid on each other for comparison. Also of critical importance is VISUAL's ability to calculate and display stability parameters' using the basic meteorological field's found in the GFS model data. This allows for the Brunt Väisälä Frequency and the Scorer Parameter to be quickly determined in a horizontal or vertical plot; extremely useful for this VPW research.

IV. RESULTS

During the time from 01 October 2003 through 31 March 2004, six strong VPW events occurred south of the Central and Eastern Alps. Each event was unique in development, persistence time and decay. That being said, the general synoptic situation and subsequent VPW response was quite similar in all six events so only one individual event will be reviewed in detail. Due to their synoptic similarities, a composite analysis of all the VPW events was compiled to determine if a general atmospheric trend was discernable for the initiation of VPW events as compared to that of the composite analysis for non-VPW events. Of concern is that this research only includes a small number of events over a relatively short period of time. Therefore, it is critical to understand how much the European winter of 2003-2004 deviated from its climatological mean.

A. 13-15 FEBRUARY VPW EVENT

1. Synoptic Overview

The synoptic situation on 13 February 2004 is meridional; with strong ridging evident at all levels over Western Europe (Figures 11 a,b,c). This ridging keeps the Polar Front Jet (PFJ) well to the north and east of the Alps. To the east, long wave troughing persists over the Balkan states, advecting in cold air to that region as indicated by widespread cumulus streets over the eastern Mediterranean. It is clear that the jet core at 300 hPa is located a fair distance away from the spine of the Alps; however, the geopotential height gradient is still fairly tight. Flow in southeastern Germany is out of the north-northwest at 60-70kt. At the surface, a cold pool of air has banked up against the northern slopes of the Alps. An extended, albeit weak, warm front from the parent low in Scandinavia is sliding in from the northwest, causing overrunning conditions. This cold pool and subsequent warm front is acting to modify the effective topography of the Alps and allows for flow to more easily ride over the Alps.

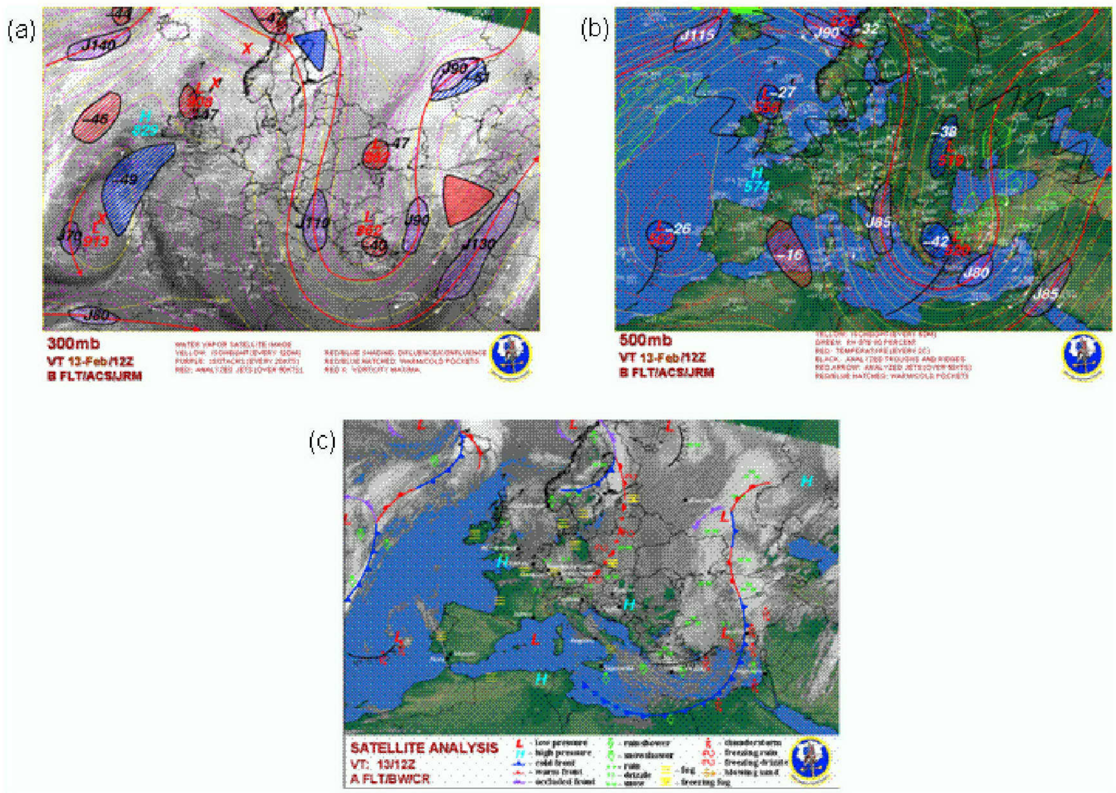

Figure 11. (a) 300 hPa (mb) upper air analysis, (b) 500 hPa (mb) upper air analysis, (c) surface satellite analysis, all valid 12z 13 February 2004. Developed by the USAFE OWS synoptician.

2. Upstream Conditions

An excellent view of the mesoscale flow just upstream of the Alps is available with the Munich sounding data. Figure 12 shows a progression from 00z 13 February through 12z 16 February. Early in the period (Figure 12a), the environment is stably stratified above mountain top level (conducive for VPW development). Flow, however, is from the north-northeast (just over 30° from perpendicular) at 35-55kt above mountain top level and increasing rapidly with height to 115kt at the tropopause. This indicates a jet max above or nearby to southeastern Germany, which may lead to wave trapping. As time goes on, the atmosphere remains stably stratified above mountain top level, with no prominent inversions above 700 hPa. A weak nocturnal inversion is visible at the surface with a much more pronounced warm frontal inversion evident at about 800 hPa (Figure 12b). Being below mountain top level, these inversions will not have a large impact on the wave response.

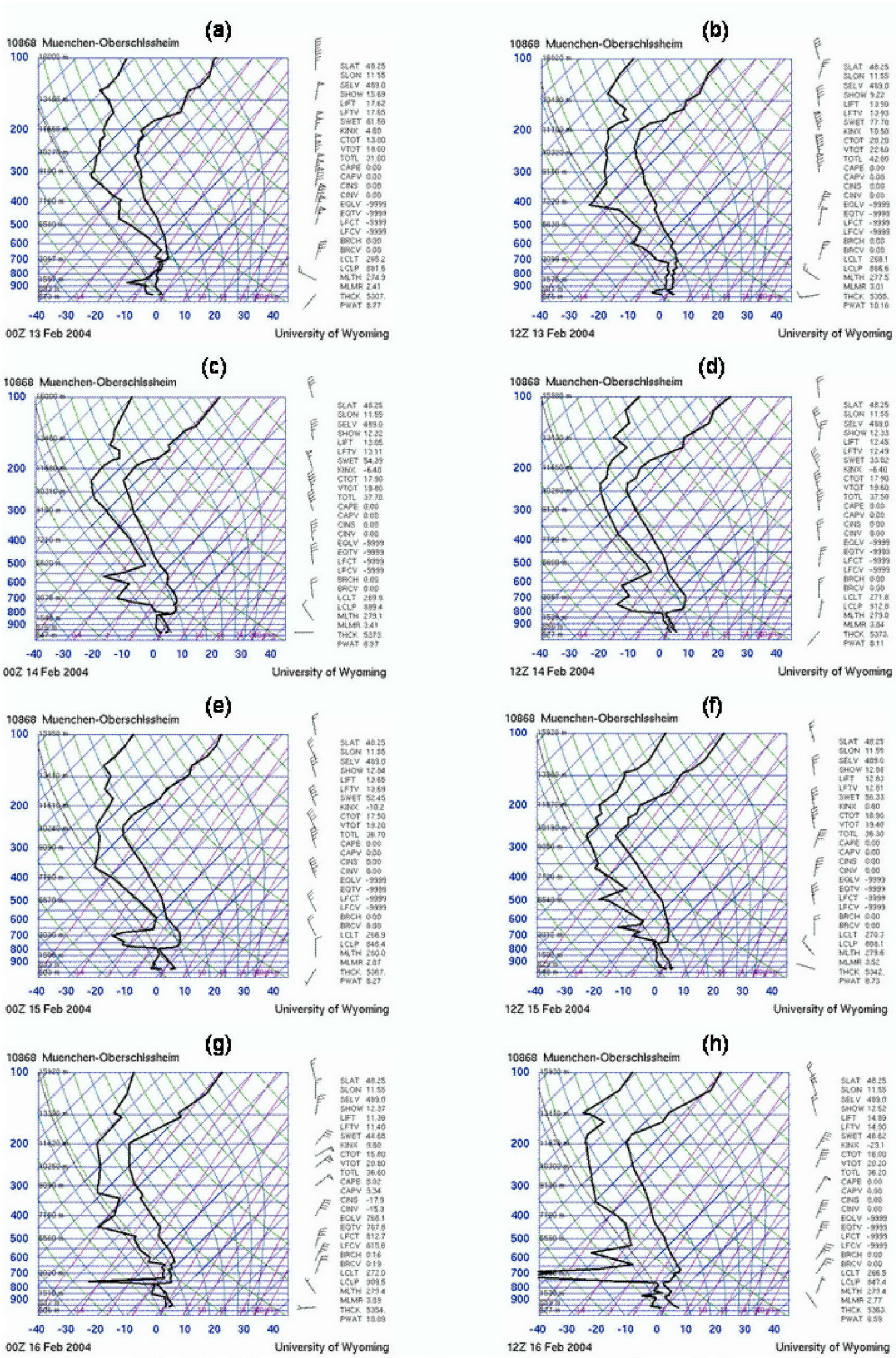

Figure 12. Munich Upper Air Soundings in Skew-T format, from 00z 13 Feb 2004 through 12z 16 Feb 2004.

Winds begin to back to more of a north-northwesterly flow and vertical speed shear decreases drastically (Figure 12c). By 12z on 14 February (Figure 12d), maximum flow is only 45kt and by 00z 15 February (Figure 12e) the flow is northwesterly above mountain top. Throughout the period, winds at mountain top level range from 17-25kt. By 12z 15 February (Figure 12f) winds begin to veer back to the north-northeast and by 00z 16 February (Figure 12g) the entire column of air has veered to a northeasterly direction and multiple inversions are present above mountain top level, indicating stability fluctuations with height (not a favorable environment for VPWs).

3. Stability

As clearly indicated by the upper air soundings, no inversion above mountain top level is present and the atmosphere is stably stratified. A simplified Scorer parameter plot (Figure 13a) also shows a favorable, nearly constant, vertical stability profile early in the period. This vertical cross-section of $\ell = N/U$ extends from Munich (left hand side) to Venice (right hand side), and shows $d\ell \approx 0$ above mountain top level (about 700 hPa). These conditions are favorable for VPW development. Stability changes drastically below mountain top level due to the strong inversion, weaker flow and backing of winds to nearly ridge parallel at the surface.

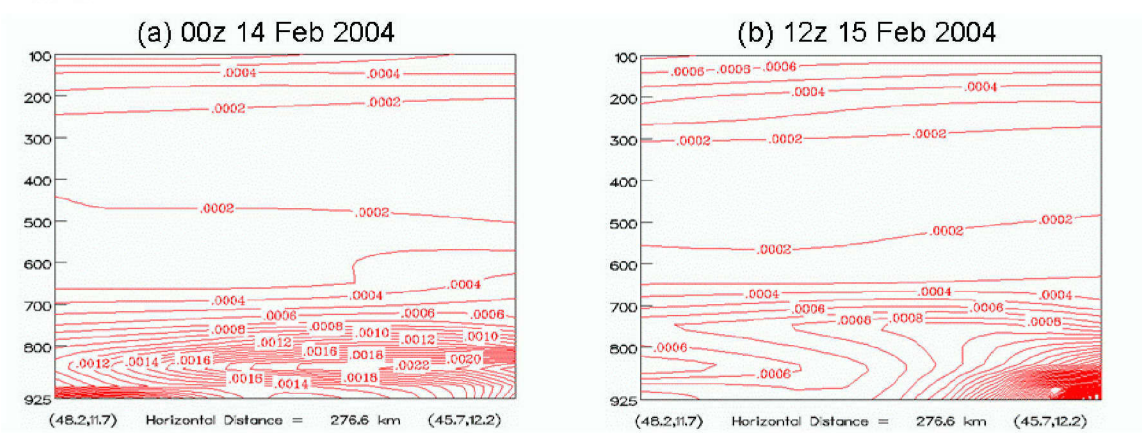

Figure 13. VISUAL vertical cross-sections of simplified Scorer parameter $\ell = N/U$ (a) during and (b) just after termination of the VPW event. Munich is the left most point, while Venice is the right most point. Note minimal change in ℓ with height above mountain top level. Perpendicular cross-barrier flow was input as 340°.

Figure 13b, which is valid just after the VPW diminished, also looks quite favorable above mountain top. The reason behind this is that winds began to veer over time, thus causing a decrease in U due to a wind direction that is no longer perpendicular to the ridge axis. Conversely, there was a considerable increase in wind speed during that time. These differences basically nullify one another and make for a similar profile, which can be misleading.

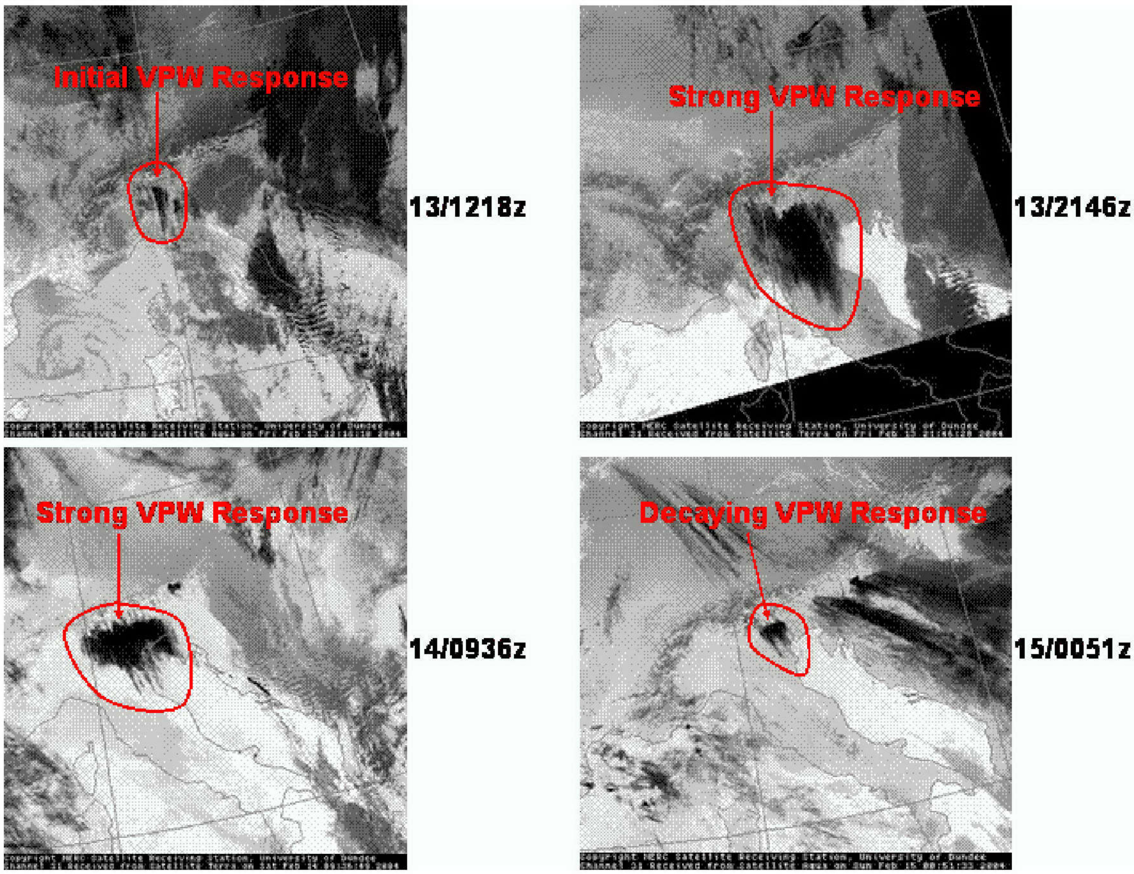

Figure 14. MODIS Terra Ch31 infrared images, 13-15 February 2004. A VPW response is clearly visible downstream of the Alps, over northern Italy.

4. Event Imagery

The end result of this flow over the Alps is the initiation of a VPW at about 12z on 13 February, becoming quite strong for at least 24 hours, then slowly decaying and disappearing entirely by 05z on 15 February. Several MODIS images in Figure 14 are able to give a relative idea of the life cycle of this event. The initial response is rather limited in scope, most likely because the synoptic flow is not entirely favorable. Early in the period, winds are just beginning to shift

to the north-northwest and maximum speeds at Munich are about 85kts. It is reasonable to assume that the VPW begins well to the west, as far away as possible from the jet maxima (synoptic propagation). As the jet maxima slides eastward, the coverage of the event becomes much greater. The VPW event begins to decay late on 14 February as the ridge axis becomes more and more positively tilted and imbedded short waves act to weaken the ridge.

Also of note in the imagery is a trapped wave response to east of the VPW event. The trapped response likely occurred for a couple of reasons. First, a closer proximity to the jet stream, thus stronger flow increasing more rapidly with height. Secondly, the warm frontal inversion is likely above these less significant mountains, thus providing a stable layer to trap the waves. This would lead to a Scorer parameter maximum just above mountain top level, with a rapid decrease vertically (conducive for trapped lee waves).

B. COMPOSITE OF ALL SIX VPW EVENTS VS. NON-VPW EVENTS

Using the VISUAL program, a composite of all GFS analyses in the date/time group of Table 2 was developed to provide the average conditions during VPW events. The same process was also done with GFS analyses in the date/time group of Table 3 to produce a composite of non-VPW events.

Looking at the geopotential height (GHT) composites in Figure 15, it is clear that several different synoptic regimes are represented. The VPW composite (Figure 15a) shows meridional flow with a ridge axis extending from its 5800 m high near the Pyrenees northward towards Scandinavia. Although the geopotential flow is similar, the non-VPW composite (Figure 15b) is less meridional, has a westward displacement of the ridge axis and lower GHT values throughout Europe. Due to seasonal smoothing, the winter composite (Figure 15c) has little to no meridional component and has the lowest GHT values. Over the Munich area, GHT values range from about 5700 m during the VPW composite, all the way to 5530 m during the winter mean. This clearly indicates much warmer air is present over the region during VPW events.

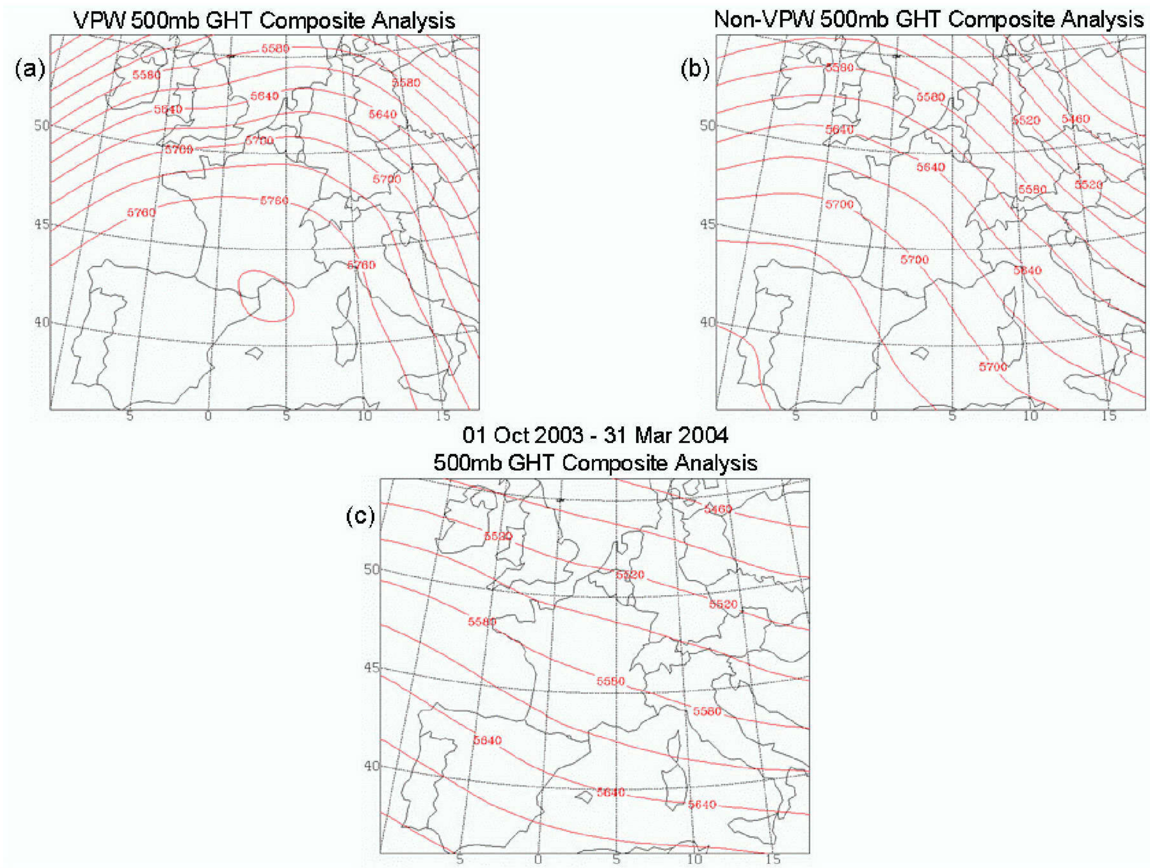

Figure 15. VISUAL composite analyses of 500 hPa (mb) GHT from (a) VPW events, (b) non-VPW events and (c) the entire 2003-2004 winter season.

Moving down to the surface, Figure 16 shows a composite comparison of mean sea level pressure (MSLP). The VPW composite (Figure 16a) clearly indicates dominant high pressure over the western Alps with a very tight gradient to the north. The high to the north of the Alps may be indicative of low-level blocking upstream. There is also leeside troughing over Italy. Both are consistent with wave activity. The non-VPW composite (Figure 16b) has a similar synoptic look, although high pressure is considerably weaker and the gradient is a bit looser to the north. The winter mean composite (Figure 16c), however, has a very different structure, with no distinguishable high pressure in the region and a very loose gradient. Due to its frequent occurrence during winter months, evidence of a Genoa Low is apparent on this chart, just south of the Alps. It is obvious from the winter composite that the VPW and non-VPW composites are rather rare events.

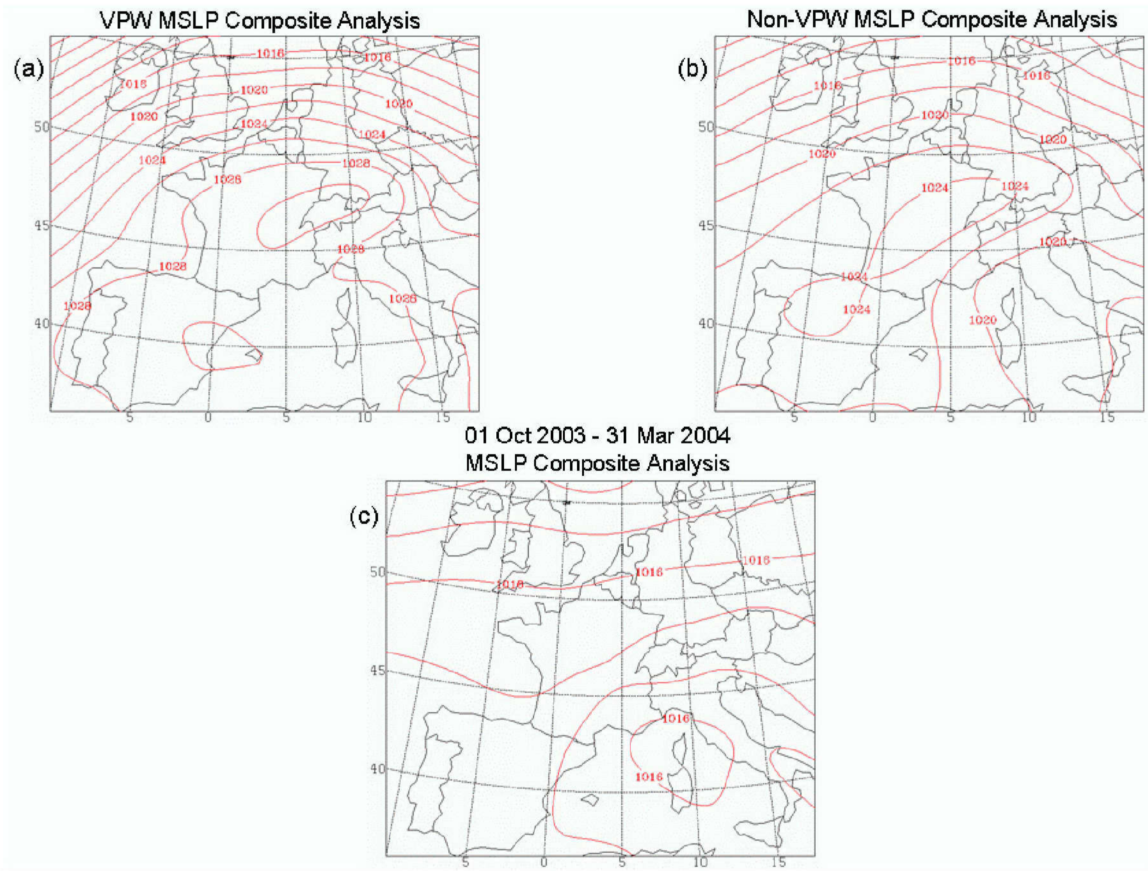

Figure 16. VISUAL composite analyses of MSLP (hPa) from (a) VPW events, (b) non-VPW events and (c) the entire 2003-2004 winter season.

Another telling parameter is the vertical upstream profile. Figure 17 shows 3 composite Skew-T's at the same location as Munich's observed upper air soundings. It is obvious that the wind profiles for both VPW (Figure 17a) and non-VPW (Figure 17b) events are out of the northwest with minimal direction and speed sheer in the vertical (conducive for deep propagation). It is interesting to note that the winter mean composite (Figure 17c) has a very similar wind profile; however, the variance is quite high compared to that of the VPW and non-VPW plots. A key difference between the 3 composites is the thermal structure, which is further highlighted in Figure 18. Compared to both the winter season and non-VPW composites, the VPW thermal structure is much more stable below mountain top level. This is indicative of a relatively cool airmass underneath a warm mid-level airmass (i.e. overrunning). Also apparent are much warmer mid and upper level tropospheric temperatures. This warmer column of air

corresponds properly with ridging over Western Europe, resulting in higher geopotential heights and more dominant surface high pressure (Figures 15a and 16a, respectively). On the other hand, the VPW composite has much cooler temperatures at tropopause level and into the stratosphere. This is a clear indicator of a higher than normal tropopause and that the location is equatorward of the PFJ. Of note, dewpoint temperature is contoured in black and data corruption of the moisture fields did not allow for this parameter to be plotted properly. This was not a significant problem since VPWs do not need a good deal of moisture to be able to develop a cloud signature.

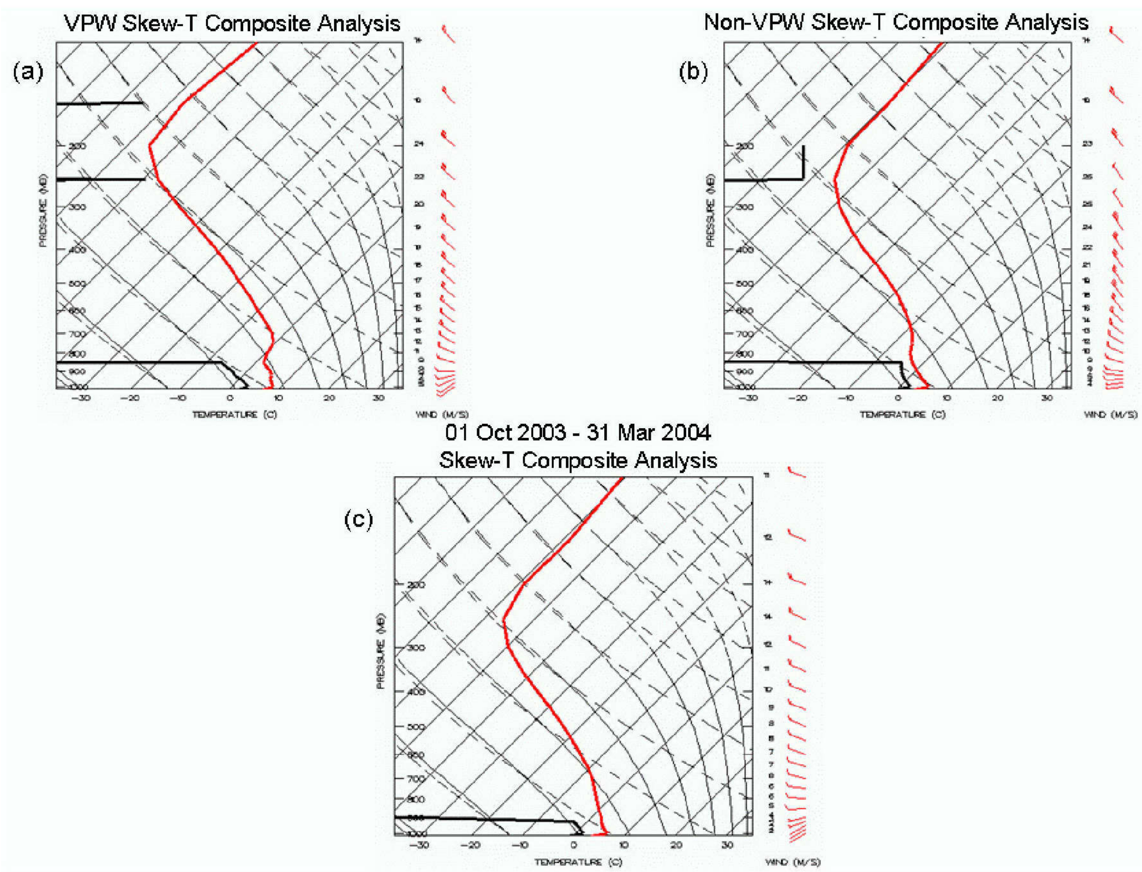

Figure 17. VISUAL composite analyses of Skew-T's from (a) VPW events, (b) non-VPW events and (c) the entire 2003-2004 winter season. Note: wind barbs in knots while text is in ms^{-1}.

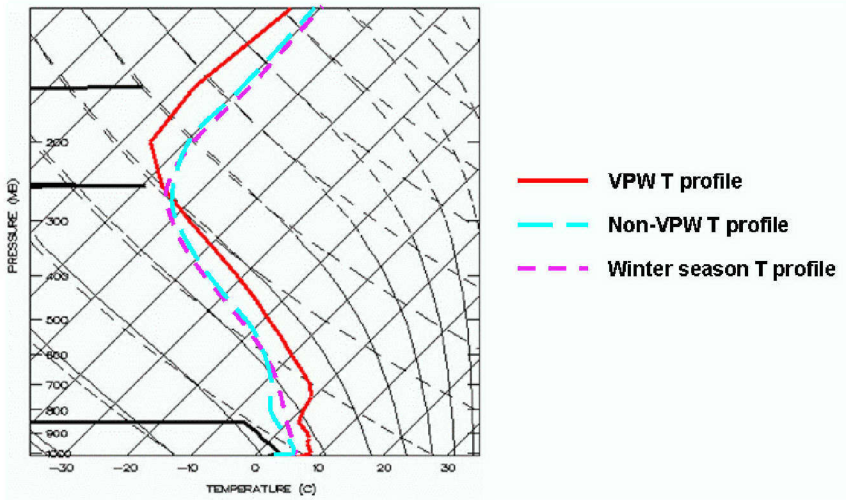

Figure 18. Visual composite overlay of temperature profiles from VPW events, non-VPW events and the entire 2003-2004 winter season.

Much like in the example February VPW case, composites of the simplified Scorer parameter varied only slightly between VPW events (Figure 19a) and non-VPW events (Figure 19b). Note the deeper layer (less abrupt) change in ℓ for the non-VPW events.

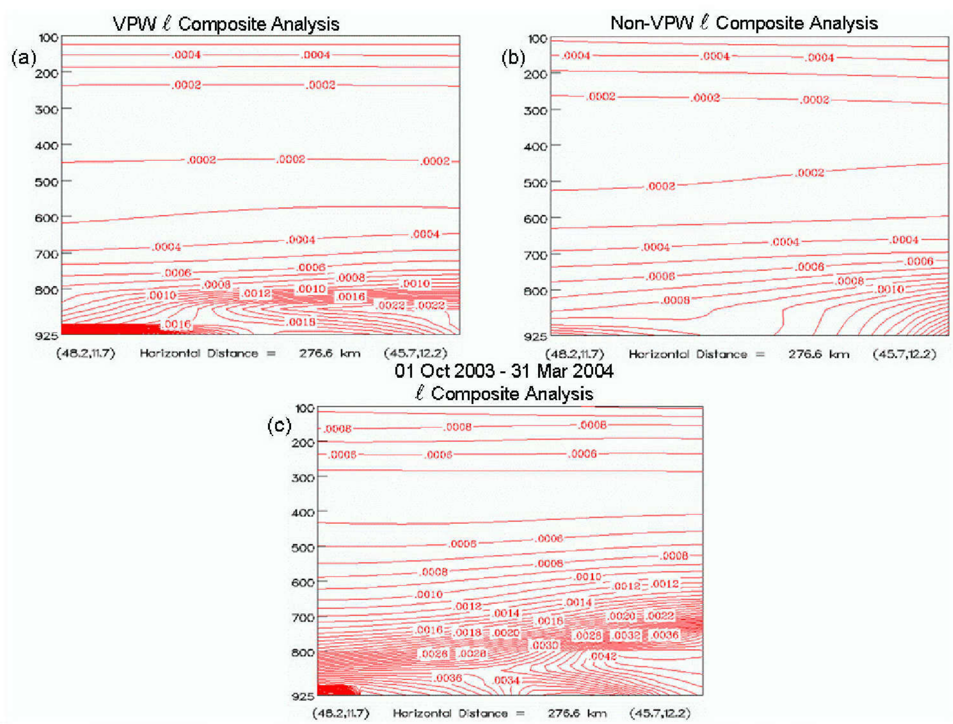

Figure 19. VISUAL vertical cross-sections of simplified Scorer parameter $\ell = N/U$ (units m^{-1}) during (a) VPW events, (b) non-VPW events and (c) the entire 2003-2004 winter season. Munich is the left most point, while Venice is the right most point.

This suggests that the inversion in non-VPW events tends to occur above mountain top level. This structure is also evident on the composite soundings (Figure 18). This leads to the assumption that the Scorer parameter is not the best tool in forecasting VPWs. To the USAFE OWS forecaster, the Scorer parameter is an unfamiliar variable that can only be found with tedious work, so is of no significant use to him/her on a daily basis.

C. EUROPEAN WINTER OF 2003-2004 CLIMATE OVERVIEW

As was shown with the composite comparisons, the synoptic situation plays an integral role in VPW development. The synoptic pattern changes from day to day and can vary greatly from year to year depending on global atmospheric and oceanic changes.

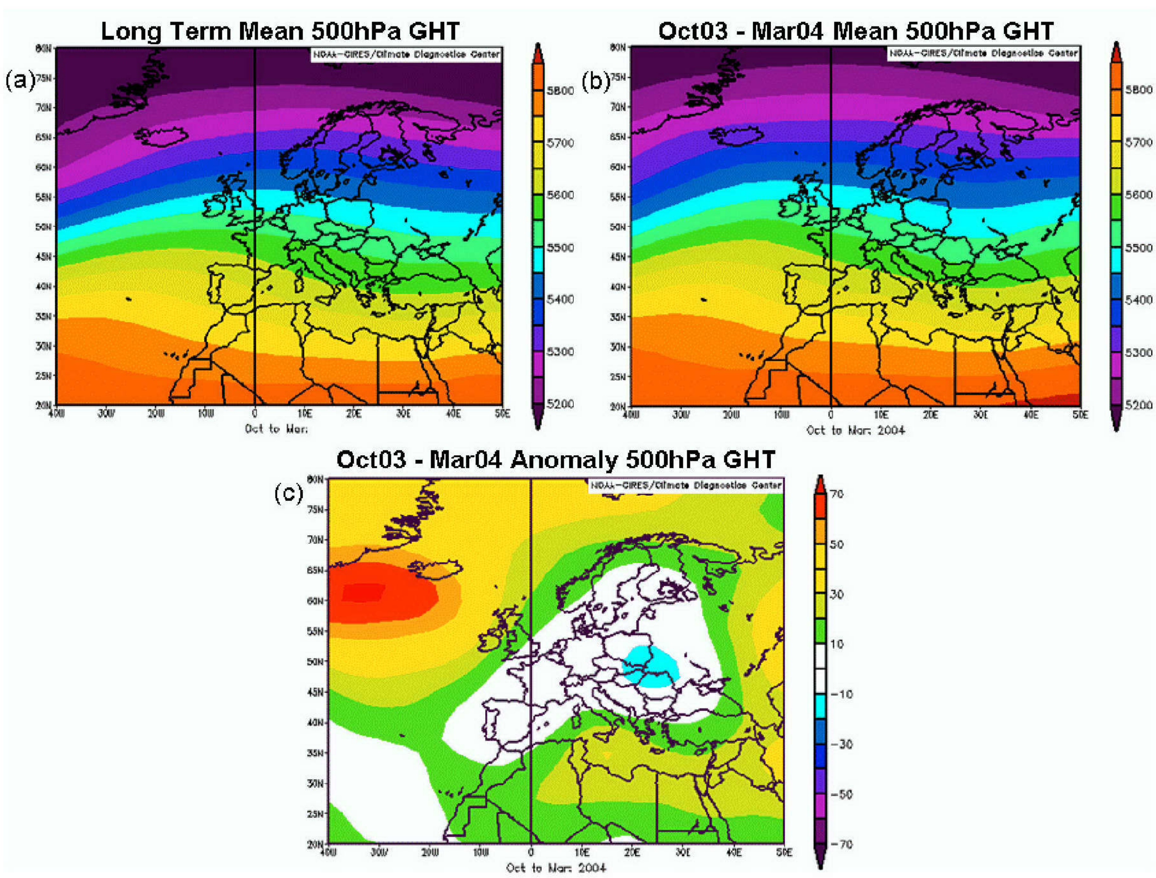

Figure 20. (a) 500 hPa GHT LTM, (b) winter season 2003-2004 mean and (c) winter season 2003-2004 anomaly. (From NOAA-CIRES, Mar 2005)

Because this research only includes a small set of VPW cases over a relatively short timeframe, it is important to validate that the 2003-2004 season is not an anomalous year compared to that of the long term climatological mean (LTM). By showing the similarity we can deduce that the winter season 0f 2003-2004 was not an anomalous year for VPW development. An excellent way of validating the climatology as far as VPWs are concerned is to look at the GHT diagrams. GHT is temperature dependent and provides a good estimation of geopotential flow. Figure 20 compares the 500 hPa GHT LTM and 2003-2004 winter season mean as well as shows the anomaly (LTM minus Mean) that exists between the two. The anomaly is quite useful because it accentuates differences between the mean diagrams that are difficult to determine by just looking at the two diagrams. It clearly indicates a weaker Icelandic Low (anomalously high heights indicated in red), however, continental Europe shows little to no climatological anomaly (as indicated by the white area).

D. RULES OF THUMB

Appendix B shows the current USAFE OWS standard operating procedure (SOP) rules that forecasters are to use when predicting mountain waves. These rules were extracted from AFWA TN-98/002, the primary Air Force weather forecasting manual. The problem with much of this guidance is that it was developed to properly forecast trapped lee waves, not the more severe VPWs. A good deal of what is known about trapped lee waves, and the atmospheric conditions that excite them, is relevant for VPWs. However, it is the atmospheric conditions that separate these waves that are critical, not well documented and thus improperly forecast. The observational and model information obtained on the 6 VPW events to the lee of the Alps during the winter of 2003-2004 has provided a wealth of upstream and synoptic-scale data and the basis for updated VPW forecasting rules of thumb. Some of the current rules in Appendix B have been found to be accurate for VPWs but need a more defined range. Other rules, however, only focus on trapped lee waves and need to be fully revised to include parameters which are also pertinent to VPWs.

1. Coinciding Rules

a. Normal Flow

The first rule is that the wind is normal to the mountain range (this rule did not specify what level, but it was assumed to be mountain top level flow). Any deviation from perpendicular will decrease the potential of VPW development. This statement holds true for both VPWs and trapped lee waves. However, because the large scale ridge-axis of the Alps is not constant and there is such varied terrain acting to complicate the flow, a wide range of flow directions may be favorable. It was found that winds at mountain top level ranged anywhere from westerly to northerly. More westerly flow was evident in VPW development in Eastern Austria while more northerly flow was observed in VPWs over Italy, due primarily to ridge axis orientation differences. One item not mentioned previously is that winds below mountain top level did not have to be perpendicular to the ridge axis. In fact, most of the time there was a drainage wind in the opposite direction of the mid level flow.

b. Vertical Flow Profile

Winds gradually increase throughout the vertical profile and there is little directional shear. This statement is much more accurate for VPWs than for the intended trapped lee waves. The general rule of thumb is that winds increase by less than a magnitude of 1.6 from mountain top level (700 hPa) to 2000m above (~500 hPa). The 6 VPW events showed an average increase from 700 hPa to 500 hPa by a magnitude of 1.52, ranging from 1.06 to 1.82. However, there is little guidance on directional shear other than, minimal is favorable. The 6 VPWs averaged 15° of shear from 500 hPa to 700 hPa, ranging from 0° to 50°. In every case the upper level wind was more northerly than the lower level wind (more westerly), indicating veering with height, thus warm air advection.

c. Thermal Structure

Thermal ridging at or above the mountain top level is another criterion currently used and found to be a valid parameter. This statement can be expanded to include ridging extends across Western Europe at all levels in

the troposphere, with a dominant surface high evident in the France/Switzerland area. Average 1000-500 hPa thickness over Munich during VPW events is 5455 m compared to the climatological winter mean of 5370m. Another good guide is temperature advection in the low to mid levels. 700 hPa temperatures range from 0.4°C to -14.1°C with the average being a balmy -3.9°C, much warmer than climatology. The 500-hPa temperatures range from -14.7°C to -27.1°C with the average during VPWs being -16.5°C. Warm air advection continues for the duration of the event. If cold air were to advect into the region the environment would destabilize, thus decaying oscillatory forces.

2. Differing or Previously Unmentioned Rules

a. Topographic Characteristics

There are a few discrepancies with the current criteria as well as several other parameters that must be accounted for. First, “the mountain range does not have another range immediately downstream”, holds true primarily for trapped lee waves. VPWs, however, are a larger scale phenomenon, thus develop due to the general size and structure of the entire range. For example, traversing the Alps from north to south would result in dozens of ridges and valley’s. However, the VPW reacts to a smoothed topographic barrier due in part to the large-scale forcing and the effective topography. An important point missed with this rule is to provide a general guideline as to what mountain ranges can excite mountain waves. Trapped lee waves have been observed to develop in the lee of hills with as little as 300m elevation gain (Queney *et al* 1960), so obviously it would be unreasonable to list all terrain in Europe that can excite trapped lee waves. VPWs, on the other hand, need at least 800-1000m elevation gain. The primary focus of this research was on the Alps, although, a list of mountain ranges that excited VPWs during the winter of 2003-2004 was compiled. This cannot be assumed to be all encompassing but provides a basic idea of what ranges to focus on in Europe for possible VPW development.

Mountain ranges exciting several VPW events during winter 2003-2004:

Alps (primarily northwesterly flow, occasionally southeasterly flow)

Pyrenees (northerly or southerly flow)

Corsica & Sardinia (westerly flow)
Appennines (southwesterly flow)
Carpathians (westerly flow)
Iceland (numerous flow directions)
Kjolens (westerly flow)

Mountain ranges exciting one VPW event during winter 2003-2004:

Transylvanian Alps (northerly flow)
Balkan Mountains, Bulgaria (northerly flow)
Massif Central (westerly flow)
Sierra Nevada, Spain (northwesterly flow)
Cordillera Cantabrica, Spain (northwesterly flow)
Black Forest, Germany (westerly flow)
Erzgebirge, Germany (northwesterly flow)
Pennines, England (westerly flow)

b. Jet Stream

Relevant for trapped lee waves but not for VPWs is that an approaching jet max enhances the probability of wave formation. VPWs need a weakly sheared environment because the stronger the flow becomes aloft the greater the chance a wave duct will develop and act as a barrier for further vertical propagation. Average maximum speed in the Munich soundings was 58kt, with a range from 39kt – 82kt. The higher end of this range occurred at the beginning and end of a prolonged VPW event (3-6 February) and had multiple wave crests as well as a trapped lee wave response imbedded within the event. These increased winds are indicators of only a marginally intense VPW. The most intense wave formations occurred when the maximum upstream wind was less than 70kt.

c. Stability

The stability of the atmosphere is a crucial piece of both the VPW and trapped lee wave forecasting puzzle. The current USAFE OWS rules have no mention of stability and thus ignore a critical variable that delineates VPW vs. trapped lee wave response. The composite VPW temperature profile (Figure 18) shows a warmer and more stable near surface atmosphere. Most of the profiles

have either a nocturnal inversion or warm frontal inversion allowing for easier lift over the terrain. Above mountain level, however, the Figure 18 indicates a conditionally stable environment up to the tropopause. This uniformly stably stratified environment allows for wave propagation in the vertical. Half of the Munich upper air observations during VPW events show weak inversions (about 15 hPa thick), while the other half have no inversion whatsoever above mountain top.

3. Summary of VPW Rules for the Alps

Summarizing the information above, this is a list of the rules developed for forecasting VPWs in the lee of the Alps:

Wind flow:

- Normal to ridge axis at mountain top level (275°-360°)
- Typically weak and with a south-southwest direction in the lowest levels (consistent with flow blocking)
- Speeds of 15-45 kts at 700 hPa
- Speeds of 25-65 kts at 500 hPa
- Magnitude of 500 hPa wind is less than 2 times that of 700 hPa wind, typically about 1.5 times
- Slight veering (clockwise turning) with height. Typically, a 15° difference between 700 hPa and 500 hPa
- Max upstream flow <70kt for severe-extreme VPW, <85kt for moderate-severe VPW

Thermal/Stability Structure:

- Ridging across Western Europe
- Strong high pressure over Western Europe, typically centered over France or the Bay of Biscay.
- Conditionally stable atmosphere above mountain top level
- No deep inversion above mountain top level
- No cold air advection in the low to mid levels. 700 hPa temps average -4°C, while 500 hPa temps average -17°C.

E. WINTER 2004-2005 VPW FORECAST

The rules of thumb above were developed using a limited data set. Therefore, it was imperative to apply these rules to an independent data set to verify their effectiveness. To obtain the most thorough archived data available the independent data set used was the most recent winter season (2004-2005). Dates used in this verification were from 01 October 2004 through 07 March 2005. This is a nearly identical timeframe as the data the rules were developed form, however, March has been cut short because observed and model data was not available by publishing time.

During the 2003-2004 season satellite imagery was used first to determine when a VPW occurred. In this forecast, model data and Munich upper air soundings were the primary tools, just like that available to the operational forecaster. The satellite imagery was then used to verify the forecast. To speed a forecast process that included over 300 upper air observations and model 00-hr analyses (over 150 days, twice a day), an assembly line style method of forecasting was incorporated by looking at just one data type over the entire period and then moving onto another data type after narrowing the scope of times to a more manageable number.

1. Upper Air Observation Analysis

Due to their web based archive structure and wealth of information, the upper air observation data was easiest to analyze first. Munich Skew-T's were able to be analyzed one month at a time, quite rapidly. Any profile that did not meet 700 hPa, 500 hPa flow or max speed ranges was determined to have no probability of exciting a VPW. This quick analysis deleted over 75% of the data hours. A much smaller data set was then reanalyzed to determine if vertical speed and directional shear, thermal advection and inversion profiles met our new criteria. After doing so, about 40 of the original 300+ data times remained to be further analyzed on the synoptic scale.

2. Synoptic Scale Model Analysis

Time constraints did not allow for the GFS REGRID model data to be used for the 2004-2005 winter season. However, because this study was not a

measure of model skill and only the 00-hr forecast analysis was used, replacing GFS with another global model capable of providing a 00-hr analysis would suffice. Available to the NPS Department of Meteorology was the global NOGAPS 00-hr analysis (NOGANAL). The NOGANAL plotted all the basic parameters that a synoptic scale turbulence forecaster would need to develop a VPW forecast. The primary levels used in this forecast were the mean sea level pressure and 500 hPa geopotential heights. Multiple data times were deemed unfavorable due to drastic departures from the general rules of thumb (i.e. low pressure over Western Europe or ridge axis extending to the south and east of the Alps rather than to the north).

3. Forecast Results

After the upper air observation and model analysis was complete, only 16 data times remained (Table 5). These times represent an initial forecast of VPW development. Lack of temporal observation or model resolution and minimal forecast preparation time causes these forecasts to be point in time rather than to have a valid range.

	Oct-04	Nov-04	Dec-04	Jan-05	Feb-05	Mar-05
DD/HHz VPW Forecast	02/00z	16/12z		04/12z	11/00z	
		17/12z		07/00z	11/12z	
		18/00z		07/12z	12/00z	
		18/12z		08/00z		
				10/00z		
				14/00z		
				14/12z		
				15/00z		
				31/12z		

Table 5. Date/Time during winter 2004-2005 that a VPW was forecast.

With the forecast complete, it was then possible to analyze the MODIS satellite imagery. The more than five months of analysis resulted in 7 definitive VPW events and 2 suspect events (Table 6). The suspect events appeared because only MODIS imagery was available for satellite analysis. Had an

archived METEOSAT loop been available, a definitive answer as to the development of a VPW on those dates would have been possible.

Event #	Year	Month	Start Date/Time	End Date/Time	Event Duration
			(DD/HHz)	(DD/HHz)	HH
Definitive Events					
1	2004	Nov	16/11z	16/21z	10
2	2004	Nov	17/20z	18/20z	24
3	2005	Jan	04/10z	04/18z	8
4	2005	Jan	07/20z	08/05z	9
5	2005	Jan	09/20z	10/00z	4
6	2005	Jan	31/09z	31/21z	12
7	2005	Feb	11/01z	11/18z	17
Suspect Events					
8	2004	Oct	02/06z	02/10z	4
9	2005	Feb	12/06z	12/10z	4

Table 6. VPW events south of the Central and Eastern Alps. Dates of analysis were 01 Oct 2004 thru 07 March 2005.

Comparing the forecast to the VPW event verification, there is a strong positive forecast correlation. First, there were no definitive or suspect VPW events that went unforecast. Second, there were only four forecasts (7 Jan 00z, 14 Jan 00z, 14 Jan 12z and 15 Jan 00z) that saw no VPW activity, which means an acceptable false alarm rate (25%). In fact, this false alarm rate could drop to 6%, considering there was a trapped lee wave event from 14 to 15 Jan. According to the USAFE OWS, a trapped lee wave would verify a mountain wave forecast. Presumably, trapped lee waves occurred on these days because the profile wind max was 80-84kt. The developed rules of thumb state that the range is valid up to 85kt for a moderate to severe VPW, however, stronger VPWs occur when max winds are much lower. This indicates that the 85kt threshold may be a little high but there is not enough data to fully evaluate it yet.

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V. CONCLUSIONS/RECOMMENDATIONS

Overly generalized forecasting rules of thumb resulting from a constricted AFWA TN-98/002 are a large problem for VPW forecasting in the USAFE OWS area of responsibility. It is also evident that satellite analysis skills of VPWs are lacking due to minimal after-the-fact amendment forecasts. Air Force guidance focused on the development of trapped lee waves and did not provide the insight that USAFE OWS personnel needed to be able to properly forecast the most severe mountain waves, VPWs. The rules of thumb developed from this research have shown to help alleviate those problems with minimal added forecast effort. Appendix C is a general forecasting guide that provides basic atmospheric and topographic characteristics to delineate between VPWs and trapped lee waves.

It should be stated though, that these rules of thumb were developed with a limited data set for one mountain range during one primary flow direction. To obtain more accurate guidance an expanded data set of possibly up to one decade should be used to fully encompass the entire spectrum of atmospheric conditions that spark VPW events. Also of concern is that numerous other mountain ranges within the USAFE OWS area of responsibility excite VPWs and should also have similar research conducted on them.

Assumptions were made in subjectively determining that all the analyzed VPWs had wave breaking, thus resulting in turbulent flow. This may not necessarily be true, however, objective information would be quite difficult to obtain due to the rarity of the event as well as the possible flight hazards (severe-extreme turbulence) incurred by any aircrew that attempted to measure the turbulent flow. Studies are presently being conducted on predicting wave breaking, however, it is currently advised that any operational forecaster assume breaking and moderate or stronger turbulence if a VPW does develop.

Possible further study would be to build several more in-depth mountain range specific rules of thumb and use the basic atmospheric parameters involved

to develop an automated VPW forecasting system. These atmospheric parameters are easily extracted from model data and could develop a red (no chance of VPW), yellow (possible chance of VPW) green (excellent chance of VPW) location specific output. This type of tool would greatly help a hazards forecaster easily determine significant areas that need to be further reviewed for VPW development rather than looking at possibly dozens of VPW forecasting rules of thumb (which would begin to get quite tedious and take away from time needed to produce other synoptic scale forecasts.

For a model performance issue, it would be interesting to see if a mesoscale model would be able to accurately resolve a VPW and if that model better predicted the various atmospheric parameters that are deemed critical in forecasting VPWs. A mesoscale model initialized from a credible analysis should be superior to a global model for forecasting mountain waves due to more accurate terrain depiction, non-hydrostatic coordinate system and higher resolution. These advances would allow the mesoscale model to represent VPWs and trapped lee waves.

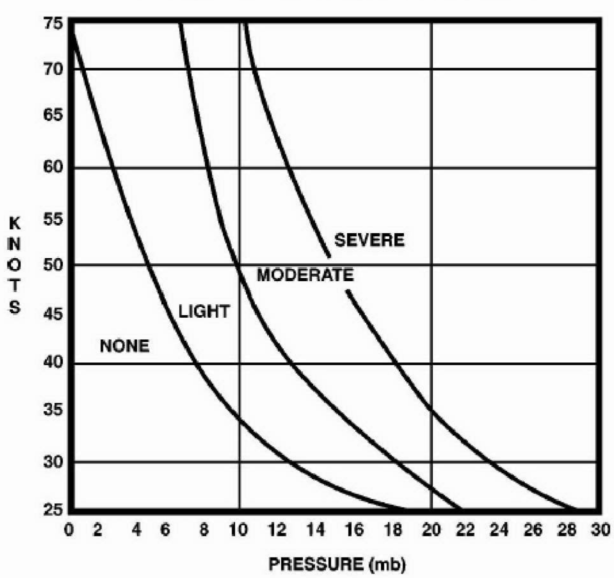
APPENDIX A – AFWA TN-98/002 MOUNTAIN WAVE FORECASTING TOOLS

These tools are the current standard Air Force guidance on forecasting mountain waves.

Low-Level Mountain-Wave Turbulence (Surface To 5,000 Ft Above Ridge Line)			
Low-Level Feature Wind Component Normal to Mountain Range at Mountain Top and > 24 kt and	**Turbulence Intensity**		
	Light	**Moderate**	**Severe**
dP Across Mountain at Surface is	See Figure 2-48	See Figure 2-48	See Figure 2-48
|dT| Across Mountain at 850 mb is	< 6°C	6°C - 9°C	> 9°C
|dT/dX| Along Mountain Range at 850 mb is	<4°C/60 NM	4-6°C/60 NM	>6°C/60 NM
Lee-Side Surface Gusts	< 25 kt	25 - 50 kt	> 50 kt
Winds Below 500 mb > 50 kt	Increase the Turbulence found by one degree of intensity (i.e., Moderate to Severe)		

Notes: (1) dP is the change in surface pressure across the range.
(2) |dT| is the absolute value of the 850-mb temperature difference across the range.
(3) |dT/dX| is the absolute value of the 850-mb temperature gradient along mountain range.
(4) Turbulence category forecast is the worst category obtained from each of the four parameters.

MOUNTAIN-WAVE NOMOGRAM



KNOTS = Maximum Wind Speed Below 500mb
PRESSURE = Sea-level Pressure Differential Across Mountains

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APPENDIX B – USAFE OWS MOUNTAIN WAVE FORECASTING RULES OF THUMB

This tool is the current standard USAFE OWS guidance on forecasting mountain waves.

1. Following criteria must be met to label a turbulence area as “Mountain Wave”:

   a. Wind normal to the mountain range. (Any variation from 90 degrees will lessen the severity of any potential mountain wave.)

   b. Thermal ridging at or above the ridgeline (i.e., no cold air advection at ridgeline). (This helps the wind to move across and downstream of the ridgeline versus the wind mixing vertically.)

   c. Gradually increasing winds throughout the vertical profile. (Significant speed or directional shear will break up a wave.)

   d. Mountain range does not have another range immediately downstream. (Secondary ranges tend to break up a wave and start a new one.)

   NOTE 1: Mountain waves tend to extend one to three degrees (60 to 180 NM) downstream from the ridge line, dependent on the ridge height and the strength of the wind blowing across the ridge top (higher ridges and stronger winds will allow the waves to extend further downstream). Bases of mountain wave turbulence will usually be SFC.

   NOTE 2: Not all wave cloud formations on METSAT imagery are associated with mountain wave turbulence. Ensure criteria in paragraph 1 are met prior to labeling the area as “mountain wave”.

2. Other Clues

   a. A temperature range from –50 to –70 degrees Celsius or less in the upper atmosphere near the suspected mountain wave zone. (-50C in the high latitudes like Norway’s Kjolen mountains and –70C in southern latitudes like the Atlas Mountains of Morocco. Also consider seasonal variation of tropopause temperatures.)

   b. Rapidly falling pressure on the lee of the mountains.

   c. Lee side gusty surface winds at nearly right angles to the range.

d. The report of lenticular and or roll clouds on the lee of the range. (ACSL, Cap, or Rotor clouds.)

e. A jet max approaching the suspected area.

f. If significant drying, “trench” may be indicated forming on the lee of the mountain range. (With this you will usually see the mountain ridge, dry air and then a cirrus shield a degree or two downstream of the ridgeline.) The most intense mountain wave turbulence is associated with stable air. Note: This phenomenon is not always apparent, especially if the atmosphere is too dry.

g. When possible, use raw sounding data above and to the lee of the ridge.

h. Mountain range that falls within the warm sector of a surface front.

3. SEVERITY: Use the table below to determine mountain wave turbulence severity.

MOUNTAIN WAVE TURBULENCE INTENSITY FOR CAT II AIRCRAFT						
Lee-Side SFC Gusts	< 25 kt	25 - 29 kt	30 - 34 kt	35 - 39 kt	40 - 49 kt	$\geq$50 kt
Turbulence Intensity	LGT	LGT OCNL MDT	MDT	MDTOCNL SVR	MDT TO SVR*	SVR

*Severity depends on how rough the terrain is and how stable the atmosphere is. E.g., the Alps are much rougher than the Cambrian Mountains of the U.K.

APPENDIX C – GENERAL MOUNTAIN WAVE CHARACTERISTICS

(Proposed update to USAFE OWS forecast guidance)

General Characteristics	Mountain Wave Type	
	Trapped	**VPW**
Flow Direc at Ridgetop (a)	w/i 30° of axis	w/i 30° of axis
Flow Direc 2000 m abv Ridgetop	numerous directions	Slight veering
Flow Speed at Rigdetop (b)	20-80 kt	15-45 kt
Flow Speed 2000 m abv Ridgetop	>1.6x(b) or << (b) and/or opposite flow direc of (b)	1.0x(b) thru 1.8x(b)
Vertical Wind Shear	large	minimal
Stability	Typically a strong inversion just abv ridgetop	Uniform stability abv ridgetop, possible inversion blo ridgetop
Mountain Width	5-100 km	50-300 km
Mountain Height	>300 m	>800 m
Lat/Lon	Global	Global
Time of year	Fall, Winter, Spring	Anytime of year, though, primarily Winter
Turbulence Intensity	Light-Severe	Mdt-Extreme
Vertical Extent of Turbulence	From near the sfc, up to and just abv wave duct	From near the sfc, up to and just abv tropopause
Satellite Signature Downstream	Numerous, evenly spaced thin cloud bands	One, large cloud band

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LIST OF REFERENCES

Allen, M. S., 2003: Evaluation of the mountain wave forecast model's stratospheric turbulence simulations. M.S. thesis, Dept of Engineering Physics, Air Force Institute of Technology, 70pp.

Dept. of Atmos. Science, University of Wyoming, cited 2005: Upper Air Sounding. [Available online at http://weather.uwyo.edu/upperair/sounding.html.]

Durran, D. R., 1986: Mountain Waves. *Mesoscale Meteorology and Forecasting*, P.S. Ray, Ed., American Meteorological Society, 472-492.

Holton, J. R., 1992: *An Introduction to Dynamic Meteorology*. Academic Press, 511pp.

Hooke, W.H., 1986: Gravity Waves. *Mesoscale Meteorology and Forecasting*. P.S. Ray, Ed., American Meteorological Society, 272-288.

Klemp, J. B. and D. Lilly, 1977: Numerical simulation of hydrostatic mountain waves. *J. Atmos. Sci.*, **35,** 78-88.

NERC Satellite Receiving Station, cited March 2005: MODIS Images. [Available online at http://www.sat.dundee.ac.uk/auth.html.]

NOAA-CIRES Climate Diagnostics Center, cited February 2005: Monthly/Seasonal climate composites. [Available online at http://www.cdc.noaa.gov/.]

Nuss, W. A. and S. Drake, 1991: *VISUAL: Meteorological diagnostic and display program*. Naval Postgraduate School, 51pp.

Nuss, Wendell A. and Titley, David W., 1994: Use of Multiquadratic Interpolation for Meteorological Objective Analysis. *Monthly Weather Review*, **122**, 1611-1631.

Queney, P., G. Corby, N. Gerbier, H. Koschmieder and J. Zierep, 1960: The airflow over mountains. WMO Tech. Note 34, 135pp.

Reymann, M., J. Piasecki, F. Hosein, S. Laraee, G. Williams, M. Jimenez and D. Chapdelaine, 1998: Meteorological techniques. AFWA Tech. Note AFWA TN-98/002, 242pp.

Scorer, R. S., 1949: Theory of waves in the lee of mountain. *Quart. J. Roy. Meteor. Soc.*, **75,** 41-56

Smith, R. B., 1977: The steepening of hydrostatic mountain waves. *J. Atmos. Sci.*, **34,** 1634-1654.

Sterner, R.,/Johns Hopkins Applied Physics Laboratory, cited January 2005: Version 2 Color Landform Atlas. [Available online at http://fermi.jhuapl.edu/states/.]

UCAR, cited March 2005: Mountain waves and downslope winds. [Available online at http://meted.ucar.edu/mesoprim/mtnwave/.

UCAR, cited March 2005: Operational Models Matrix. [Available online at http://meted.ucar.edu/nwp/pcu2/index.htm.]

Wurtele, M. G., A. Datta and R.D. Sharman, 1993: Lee waves: Benign and malignant. NASA Contractor Report 186024, 23pp.

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